

NETWORK GENERATION FOR SIMULATION OF MULTIMODAL LOGISTICS SYSTEMS

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ABSTRACT

Simulation of multimodal logistics systems might require realistic modeling of the transportation networks (road, rail, air, and waterways), e.g., when evaluating the use of Automated Guided Vehicles (AGVs) on public roads or the combined use of trucks and Unmanned Aerial Vehicles (UAVs) in humanitarian logistics with disturbed infrastructure. In this paper, we propose a simulation add-on to automatically generate infrastructure networks for multimodal logistics, including logistics locations (e.g., warehouses and terminals) and various transport modes (e.g., trucks, AGVs, and UAVs) with corresponding behavior. The proposed methodology allows for various levels of accuracy and opens up possibilities for simulating physical flows of various transport modes, congestion, stochastic behavior of the network, and variable transport demand over time in a simple, quick, and accurate way. We illustrate our approach using two case studies corresponding to the examples given above with AGVs and UAVs.

1 INTRODUCTION

The analysis of supply chains is gaining more and more relevance due to challenging sustainability goals and promising concepts, such as zero emissions logistics (Punte et al. 2019), synchromodality, and Connected and Automated Transport (CAT). Synchromodality is a type of multimodal freight transport that allows for a dynamic choice of the transport mode depending on actual circumstances, and strives for a well-synchronized, interconnected, and integrated transport network (Tavasszy et al. 2017). CAT is an area of technology aiming for fully automated vehicles (or vessels), potentially connected to their manufacturers, third-party services, the infrastructure, or other users and vehicles or vessels (European Commission 2017). The latter is expected to increase safety and efficiency for all transport modes (Meyer et al. 2019).

To study the benefits of new logistics concepts as those mentioned before, we need to model the transportation networks (road-, rail-, air-, and waterways), which might require varying degrees of accuracy. For example, a simulation study of a large transportation network connecting a port with various hinterland hubs and distribution centers might focus on the choice of transport mode at specific nodes in the network, and requires less accuracy in the modeling of the infrastructure. On the other hand, a simulation study focused on the impact of automated vehicles on traffic congestion and freight operations at an airport requires a more accurate representation of the road network and vehicle behavior in that area. An accurate representation of the infrastructure might also be required for a simulation study on humanitarian logistics, to model the damages to the infrastructure and its impact on the humanitarian operations (Çelik et al. 2015).

Considering these trends and insights, we propose in this paper a simulation add-on that automatically generates infrastructure networks for multimodal logistics. Based on only the coordinates of the area and a few specifications from the user, the add-on creates a realistic network in a data-driven manner. The add-on is able to generate roads, railways, and waterways based on OpenStreetMap (OSM) data, and is able to

insert logistics locations at specified coordinates in the network. Moreover, we embed various vehicles and vehicle behaviors in the add-on, such that multimodal logistic cases can be analyzed directly. The add-on can be used in general purpose Discrete Event Simulation (DES) software packages, i.e., packages not specialised in microscopic traffic simulation. In our case, we implement the add-on in Technomatix Plant Simulation from Siemens. On the one hand, the automatically generated networks achieve a level of detail that is close to microscopic traffic simulation with simple vehicle behavior (e.g., distance control, turn penalties, congestion). On the other hand, we can easily study the macroscopic KPIs on logistics, planning, and routing decisions, as typically supported by these DES applications.

The contribution of this paper is the development of this comprehensive network generation add-on. To show the wide applicability and scalability, we provide two illustrative cases. The first case shows the simulation of humanitarian logistics in a disaster area, and the second demonstrates the analysis of dispatching and routing policies in a port area. Our approach opens up possibilities for simulating physical flows of various transport modes, congestion, stochastic behavior of the network, and variable transport demand over time in a simple, quick, and accurate way. This allows for studying all kinds of problems in future research, e.g., rich vehicle routing problems, humanitarian logistics, Physical Internet-based transportation, and the use of autonomous vehicles.

The remainder of this paper is organized as follows: Section 2 provides an overview of literature about multimodal networks, traffic simulation, and open source map data. Section 3 describes the proposed add-on and the methodology behind it. Section 4 presents the implementation of the add-on with two illustrative cases. Section 5 concludes the paper and discusses future work.

2 RELATED LITERATURE

As our simulation add-on supports the analysis of multimodal networks, we first describe various types of transportation networks. Next, we present studies on traffic simulation. Finally, we present related work using OpenStreetMap data for transport analysis.

2.1 Multimodal Networks

Freight moves through logistics networks that employ a single or multiple transport modes, called unimodal and multimodal networks, respectively. Multimodal networks are further divided into intermodal, co-modal (or combined, Reis 2015), and synchromodal networks. SteadieSeifi et al. (2014) define these as follows: An intermodal network is a type of multimodal network, using the same transportation unit (e.g., a container) for the whole transport. For example, a train performs the long-haul transport and delivers a container at a train terminal. Then, a truck picks up the same container and performs the short-haul to destination. Co-modal transport also considers two or more transport modes, but they are owned and operated by a group of collaborating shippers, such that efficiency and sustainability of each mode are maximized. Synchromodal transport is an evolution of the two, with synchronized use of multiple transport modes. Its characteristic is to select the best mode at any time (i.e., a-modal bookings) based on operational circumstances. This choice is made at the nodes of the logistics network (e.g., intermodal terminals, ports), where multiple modes are available. For an overview of intermodality, we refer to Agamez-Arias and Moyano-Fuentes (2017) and Crainic and Kim (2007). A taxonomy for the simulation of intermodal freight transportation systems is given by Crainic et al. (2018).

Synchromodality is a promising concept enhancing the flexibility of logistics operations and increasing the transportation share of railways and waterways (Tavasszy et al. 2017). However, synchromodality is still difficult to implement in practice (Pfoser et al. 2016; Tavasszy et al. 2017). Pfoser et al. (2016) identify organizational aspects (i.e., cooperation, trust, and mental shift) as the critical factors for successful adoption, and the technical infrastructure (i.e., ICT and sophisticated planning systems) as necessary enablers. These two elements support information sharing and situational awareness by all involved stakeholders, which are crucial due to the dynamic nature of synchromodality (Kurapati et al. 2017).

Finally, we see our simulation add-on as capable of modeling multimodal and intermodal networks. To achieve synchromodality, we include mathematical models for the dynamic and integrated planning of modes. Examples of such models for hinterland transport planning are given by Zhang and Pel (2016), Behdani et al. (2016), and Qu et al. (2019).

2.2 Traffic Simulation

Traffic simulation is a wide and extensively studied research field. In this section, we frame our simulation add-on with respect to established classifications and provide several examples of similar applications. For an overview of (hybrid) traffic simulation theory and software, we refer to Burghout (2004), Kotushevski and Hawick (2009), Barceló (2010), and Pell et al. (2017). The latter specifically discuss recent advances in software for real-time traffic simulation and the importance of geographic information systems to model detailed, heterogeneous networks. Traffic simulation models can be distinguished in two macro categories: static and dynamic models. For these, we use the definition of Tchappi Haman et al. (2017). Static models usually represent a large area during a specific time period, with fixed transport demand and event distribution over time. These models are mostly used to investigate interventions with respect to the transportation network and mode choice. Dynamic models usually represent a small area based on variable transport demand in the study period. These models are mostly used to study the physical flow of road traffic and the emerging congestion.

Barceló (2010) further distinguishes dynamic models in three categories: macroscopic, microscopic, and mesoscopic. Macroscopic models represent traffic as a continuous flow, similar to fluid dynamics. They are simple, easy to calibrate and with short execution time. However, they cannot represent detailed traffic behavior and performances are collected as aggregates of the traffic flow. Microscopic models describe behavior and interactions of individual vehicles, such as acceleration, lane change, and maintaining distance, to reproduce the dynamics of the system. Therefore, they generate the most accurate physical traffic flow. Mesoscopic models combine aspects of macro- and microscopic models by representing large-scale networks and coarse traffic behavior, either with individual vehicles or platoons. Moreover, they demand lower amounts of data and are more computationally efficient compared to microscopic models, although, the physical traffic flows of mesoscopic models are not as accurate.

The three categories above can be combined into hybrid or multilevel models. The resulting traffic simulation models combine the advantages of macro- and microscopic models and accurately represent traffic behavior, but are of difficult realization (Tchappi Haman et al. 2017). We define our add-on as generating dynamic, microscopic traffic simulation models, with statistical and planning capabilities for the multimodal transport of goods.

2.3 Open Source Data for Modeling Transportation Networks

For our add-on, we make use of OpenStreetMap (OSM). Data of OSM are licensed under the Creative Commons 2.0 license, i.e., the data can be edited and utilized by users if the data source is presented. There are Application Programming Interfaces (APIs) available to extract specific data into an XML format. Data can be filtered to only extract the required type of roads, waterways, areas, or buildings and their characteristics. The data structure of OSM is divided in nodes, ways, and relations, which are specified with certain tags. Nodes are geographic points with corresponding coordinates and node id, to define standalone point features. Ways consist of a sequence of nodes and represent features such as roads, railways, boundaries, or buildings. By connecting multiple nodes, a way obtains a curvature and a specific shape. Ways in OSM are automatically connected with each other if they utilize the same node. The typical tags of a way are category tag (e.g., motorway, residential, canal, or rail), one-way tag (i.e., yes or no), maximum speed tag, or lanes tag (i.e., the number of lanes). On top of nodes and ways, there are relations. These are used to define more-advanced relationships between multiple ways or nodes, for example a bus route (OpenStreetMapWiki 2021).

For traffic simulation, OSM is frequently used as geographical data source to set up detailed route networks (Zilske et al. 2015; Arellano and Mahgoub 2013; Backfrieder et al. 2013; Feldkamp and Strassburger 2014). To a lesser extent, OSM is used for the simulation of transportation problems and computational logistics. Meyer et al. (2013) present a method to build simulation models from XML-based OSM data. The approach focuses on quickly generating complex road structures and junctions, to use for the analysis of logistic processes. Matsumoto et al. (2016) model the infrastructure with OSM for the mathematical optimization of a multi-agent simulation of urban traffic. Li et al. (2017) extract the road network structure from Shenzhen using OSM and obtain a network of 70 roads after combining it with traffic data and removing isolated roads. The authors use the network to predict traffic flows using real-time data. Elbert and Friedrich (2018) create distance- and time-based origin-destination matrices using the OSM-based routing engine Open Source Routing Machine (Luxen and Vetter 2011) and use this as fixed input for their vehicle routing algorithm and for their simulation model with urban consolidation centers. Also Gutenschwager et al. (2019) present an approach to derive road networks from OSM data. The authors include traffic signals based on generic assumptions and use cell phone data of the city of Winnipeg to estimate the average speed of vehicles on an hourly basis, to simulate time-dependent travel times for vehicle routing problems.

The related literature provides interesting cases of the generation and analysis of road networks from OSM. Our contribution is that the proposed methodology is able to model multimodal logistics networks in various levels of accuracy and that it can include road, rail, air, and waterways in a quick, flexible, and simple way. Furthermore, we integrate logistics locations and various transport modes with corresponding behavior.

3 METHODOLOGY

In this section, we conceptually describe our simulation add-on. The overall process to generate a network is shown in Figure 1. The process consists of six steps. In the first step, OSM data are requested through an API. In the second step, the data are transformed such that they can be used easily within simulation software. With these data, ways (e.g., roads, waterways, railways) are created in the third step. We adopt the definition of nodes and ways from OpenStreetMap and add segments. In our simulation, a way consists of a sequence of segments between each of the nodes of a way. Specifically, the segments form the actual shape and curvature of a way by connecting the nodes (Figure 2). Thereafter, in step four, the ways are connected with each other to form a network. In the fifth step, logistics locations are created and in the sixth step, these locations are connected to the nearest segments in the network. Steps one to four are described in more detail in Section 3.1, while steps five and six are described in Section 3.2, together with the vehicles' behavior.

3.1 Conversion from OpenStreetMap to a Simulation Model

In the first step, we import the required OSM data in XML format directly into the simulation model, using the [Overpass API](#). The API request is based on the area specified by the minimum and maximum latitude and longitude, and the required type of roads, waterways, and railways. In the second step, data are transformed to easily create the network. First, we determine the size of the area in kilometers based on the minimum and maximum latitudes and longitudes. Then, we adapt the haversine formula (Robusto 1957) with r being the radius of the earth and $\pi/180$ converting the coordinates from degrees to radians:

$$X_{length} = 2r \times \arcsin \sqrt{\cos^2 \left(\frac{lat_{min} + lat_{max}}{2} \times \frac{\pi}{180} \right) \times \sin^2 \left(\frac{(lon_{max} - lon_{min}) \times \frac{\pi}{180}}{2} \right)}$$

$$Y_{length} = r \times (lat_{max} - lat_{min}) \times \frac{\pi}{180}$$

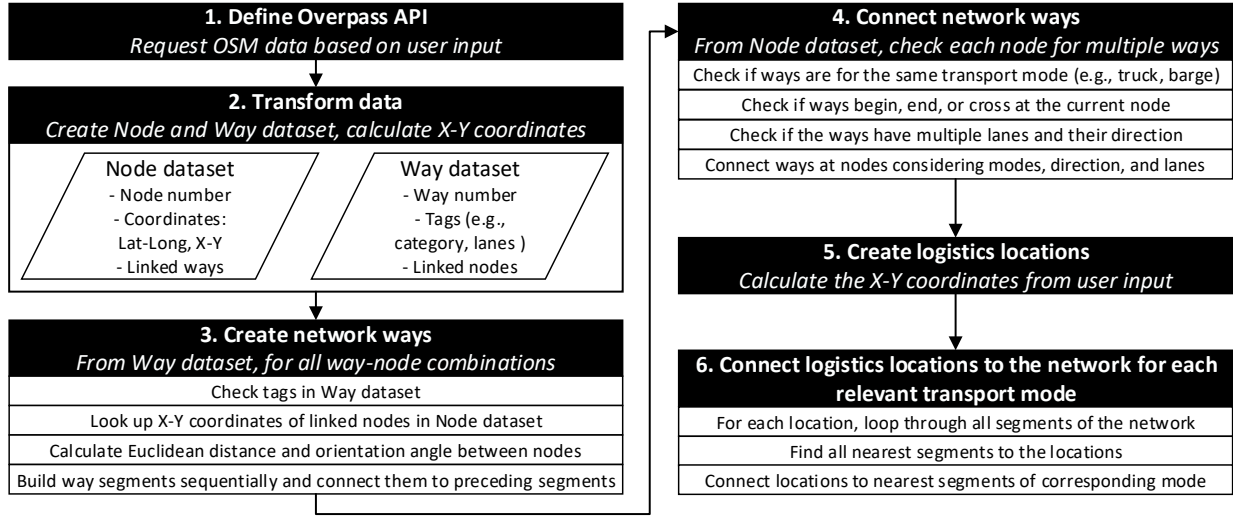


Figure 1: The process flowchart to generate the network and logistics locations, from OSM data and user input.

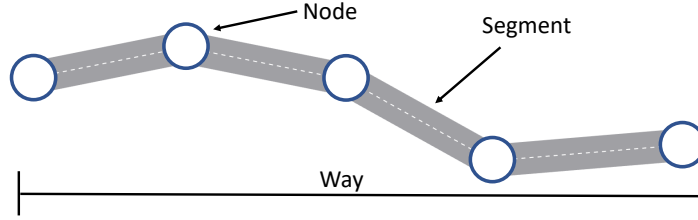


Figure 2: Representation of ways, nodes, and segments in the add-on.

In this way, we can convert the coordinate system from WGS84 (Latitude-Longitude) to Cartesian (X-Y). The X and Y coordinates of all nodes are determined by:

$$X = \frac{\text{longitude} - \text{lon}_{\min}}{\text{lon}_{\max} - \text{lon}_{\min}} \times X_{\text{length}} + X_{\text{origin}} \quad Y = \frac{\text{latitude} - \text{lat}_{\min}}{\text{lat}_{\max} - \text{lat}_{\min}} \times Y_{\text{length}} + Y_{\text{origin}}$$

Where X_{origin} and Y_{origin} are input values of the user to shift the origin of the map from (0,0). Next, a Way dataset and a Node dataset are created from the OSM data. The Way dataset consists of way numbers, tags (such as the category, one-way, or number of lanes), and the nodes paired with each way. The Node dataset consists of the node numbers, coordinates in latitude-longitude, converted coordinates in X-Y, and the ways corresponding to each node.

In the third step, all ways are generated by creating segments sequentially between the nodes of each way. The user can choose the accuracy of the network. When the user chooses a high accuracy, segments are created between each node of each way. Hence, the curves of the roads, rails, or waterways are modeled in high detail. With a low accuracy, segments are only created between the beginning and end nodes of each way and at crossings, creating a coarse network with only the minimum number of required segments composing the ways. The medium accuracy is an intermediate option, where segments are created every X nodes, at the beginning and end of each way, and at crossings. X can be adjusted to allow for various levels of accuracy. The accuracy is high when $X = 1$ and low if X is a high number. In our implementation, we use $X = 20$ for medium accuracy. Together with the possibility to choose which types of roads, waterways, and railways to model, this provides flexibility and scalability to the add-on for modeling various types of

networks. To generate the segments, first the tags are checked, to determine the transport mode, number of lanes, and the one-way property. Then, the coordinates of the segment's nodes are looked up in the Node dataset, and the polar angle and the Euclidean distance between the two nodes are determined. Based on the mode, one-way tags, and the number of lanes, corresponding road, rail, or water segments are constructed, and sequential segments of a way are connected with each other. Furthermore, based on the maximum speed, each segment also receives a route weight. The route weight will be used by vehicles to determine the shortest path. Segments with higher maximum speed receive a lower route weight as $route\ weight = 100 / maximum\ speed$. The route weight can later be adjusted during a simulation run, for example when the maximum speed could not be achieved due to congestion or damaged roads.

When all ways are constructed, ways that form intersections at nodes are connected with each other. In OSM, intersections are automatically registered when two ways use the same node. However, in the simulation model, the different segments need to be connected separately based on the specific situation of the intersection. This happens in the fourth step. Figure 3 provides an example where an intersection between a one-way and a two-way street is created. The process of connecting crossing ways occurs by looping through the Node dataset. For each node, we check all ways that cross this node; and for those who do, we check if the way only begins, only ends or crosses the respective node. Moreover, we check the way direction, corresponding mode, and whether there are multiple lanes. Considering these aspects, ways are connected to each other to form a network.

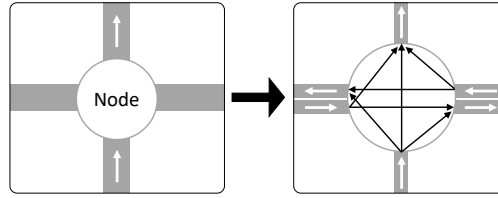


Figure 3: Example of an intersection in OSM (left) and the connections to each segment in the simulation model (right).

3.2 Utilizing The Network for Multimodal Transport

To simulate multimodal logistics utilizing the generated infrastructure, we created a library of logistics locations, and transport modes. For logistics locations, we have three classes: supply location, demand location and interface location. A supply location generates a certain transport mode in the system with a certain transportation load. Then, demand or interface locations are selected as destinations for the mode. For example, a truck exits the highway (supply) and enters a port area, to reach a warehouse (demand) or terminal (interface). For transport modes, we design 7 classes: trucks, trains, barges, planes, helicopters, Unmanned Aerial Vehicles (UAVs), and Automated Guided Vehicles (AGVs).

In the fifth step of the process flow, we generate logistics locations and connect them to the network based on their centroid coordinates, which are converted using the approach from Section 3.1. Instead of using OSM data, we manually input the centroid coordinates of each location in the simulation. In the last step, each logistics location is automatically connected to the closest network way (road, water, rail), given its current location and available transport modes. For example, a barge terminal will be connected to the closest waterway, for the arrival of barges, and the closest road, for the arrival of trucks or AGVs. The closest way of the network is selected by comparing Euclidean distances from the centroid coordinates to the coordinates of each node from each way. To reduce computation time, a maximum distance is set to rapidly discard remote ways.

We model transport modes with common and different features, based on their class. All transport modes share one feature: the shortest path algorithm. This algorithm computes the shortest path between any two logistics locations, considering the length of the segments composing the ways as well as their

route weight attribute (see Section 3.1). The algorithm does not consider congestion or turn penalties (i.e., slowing down at turns) when computing paths. Besides computing the shortest paths based on the segments' length and route weight, we model additional features for air and road modes. Air modes are freely moving in 3D space, and move in a straight line in the 2D space, with takeoff and landing in the z-dimension. Road vehicles display simple traffic behavior by modeling several aspects: goal speed, safety distance, car-following behavior, and turn penalty. The goal speed of a vehicle is set when entering a new segment, by selecting the lowest value between the vehicle's maximum speed and the speed limit. Then, we compute the safety distance using a t_{safe} -seconds rule and the current maximum speed of a vehicle on a segment: $safety\ distance = speed * t_{safe}$. Policy makers use this approximate safety distance as a rule of thumb. For us, it allows to only activate the car-following model when two vehicles are getting too close to each other, reducing computation effort. Furthermore, we can simply experiment with smaller t_{safe} values for different CAT vehicles or concepts, like AGVs and truck platoons. After vehicle $n + 1$ reaches the safety distance threshold with respect to vehicle n , the generalized car-following model by Herman et al. (1959) computes a new positive or negative acceleration value. The turn penalty activates at a relative distance from the end of the segment (e.g., 25 % of the segment). Upon activation, it reduces the goal speed by a percentage based on the angle between the current road segment and the next.

The remaining modes, namely trains and barges, have constant speed, no safety distance and no change of lane. When colliding with another mode, they simply stop and wait.

4 IMPLEMENTATION AND ILLUSTRATIVE CASES

We implemented the add-on in Siemens Tecnomatix Plant Simulation 15.1. We built a dialog window with underlying functions and tables to provide a user interface such that multimodal networks can be created with only a few inputs. The required inputs are shown in the user interface (Figure 4). By filling in the required information and clicking 'Create new network', the underlying functions are activated and a network will be created. The creation of logistics locations in the network can be activated separately. A table is required with name, type, allowed modes (e.g., road, rail, water), and latitude and longitude for each location to be imported, as discussed in Section 3.2.

To bring the visualization of the simulation model to a higher level, our implementation also allows for importing satellite imagery. It is possible that the satellite imagery of a large area is divided into multiple tiles. As input, it is required that the collected imagery spans over the same area as the imported transportation network. In that case, we can import the imagery based on the folder where the imagery is located and the number of horizontal and vertical tiles, and plot these images within the area of the transportation network.

In the following subsections, we describe two distinctive cases that illustrate the numerous possibilities of our proposed add-on. The first case is about a disaster relief operation in a large area, where research can concentrate on the analysis of different modes (especially UAVs) and the stochastic availability of the roads. The second case relates to intralogistics at a port; a smaller area where realistic modeling is key, with a focus on the representation of congestion and the impact of autonomous trucks.

4.1 Case 1: Disaster Relief Operations

The first case for which we illustrate the add-on considers the area of the earthquake and tsunami on the island of Sulawesi in Indonesia. On September 28th, 2018, a 7.4M earthquake occurred that caused liquefaction and landslides in the districts Palu, Sigi, and Donggala. The earthquake also triggered a tsunami that damaged one of the largest cities of the island, Palu. This disaster displaced more than 200,000 people, located in hundreds of camps scattered over the area. Among the main challenges for the distribution of relief supplies were the access constraints, as a lot of roads were damaged by the disaster. For further details on this case, we refer to van Steenberg and Mes (2020).

Figure 4: The dialog window with all required inputs, such that the model can easily be generated.

Based on impact estimations and assessment reports, the damage to the road network can realistically be modeled with the add-on. This offers the opportunity to simulate varying availability of road segments and analyze their effects on humanitarian logistics operations; and more specifically, to study the potential of using UAVs in humanitarian missions. For the comparison and combination of various transport modes, various aspects need to be modeled, such as damage to the road network. Figure 5 provides two screenshots of the simulation model, including the imported road network, satellite imagery, the logistics hub at the airport, trucks driving on the roads, and UAVs flying in the air to various sites with people in need. The disaster area is approximately 70 by 190 kilometers and the road network is generated at medium accuracy, resulting in 1,782 ways with 6,124 segments. It took 1 minute and 18 seconds to create this network in Plant Simulation 15.1.

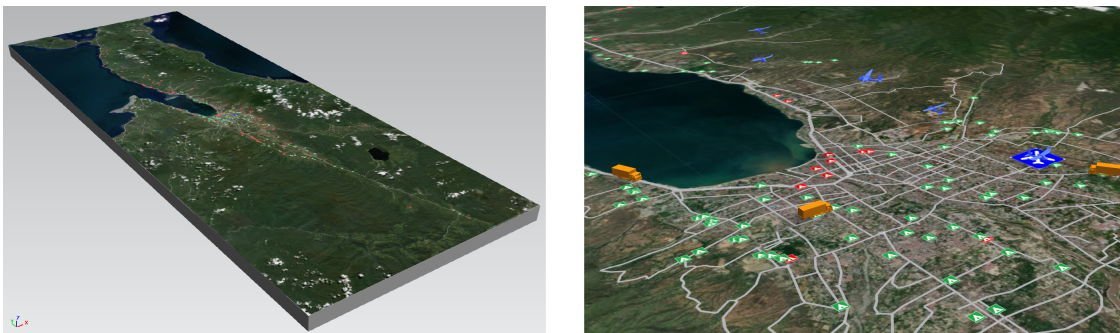


Figure 5: An overview (left) and close-up (right) of the automatically generated simulation model of the disaster area in Sulawesi.

To validate the add-on in this case, we have chosen five camp locations with displaced people in the disaster area and planned routes from the humanitarian hub at the airport to these locations. Two locations

are in the city of Palu, like the airport itself. The three other locations are located north, south, and west in the affected area. For the five routes to these locations, we have planned routes with the Open Source Routing Machine (OSRM) implemented in OSM. We compare the distances and times with the results from the add-on (Table 1). We observe that the distances of the add-on are 1.7-4.4 % shorter, which can be explained by the medium accuracy at which the network is created. With the medium accuracy, not every OSM node of each way is considered. Hence, less detailed curvature in the roads is modeled. Nevertheless, the travel times are very similar to the travel times of OSRM, with a maximum deviation of only 2 minutes on a trip of more than an hour. This shows that the combination of the medium accuracy and the vehicle behavior results in realistic travel times. Hence, it provides a good starting point for the analysis of stochastic disturbances in the network, such as with humanitarian logistics facing the unknown impact of disasters.

Table 1: Validation of distance and time of five typical routes between the OSRM and the add-on.

From Palu Airport (1)	OSRM	Add-on	Δ (%)
To Rano Balaesang (2)	132.69 km / 1:58 h	129.51 km / 1:58 h	-2.4 % / 0.0 %
To Salungkaenu (3)	66.64 km / 1:06 h	65.53 km / 1:04 h	-1.7 % / -3.0 %
To Lempelero (4)	99.84 km / 2:38 h	96.44 km / 2:39 h	-3.4 % / -0.6 %
To Poboya (5)	7.94 km / 0:16 h	7.59 km / 0:16 h	-4.4 % / 0.0 %
To Daenggune (6)	12.18 km / 0:18 h	11.69 km / 0:18 h	-4.0 % / 0.0 %

4.2 Case 2: Port Intralogistics

The second case is a study of the Port of Moerdijk (PoM), the fourth largest seaport in the Netherlands. It services approximately 14,000 vessels per year, for a total of 18.5 million tonnes of transshipment. On its area of 26.35 km², there are about 430 companies. Of these, 130 are purely logistics companies. Effective land use at the PoM is crucial. In addition, the PoM is a hub on the Flemish-Dutch Delta, close to the Port of Rotterdam. Therefore, it receives freight and ships it further inland by barge, train, truck, or pipeline. The port authority wants to reduce traffic congestion and evaluate CAT technologies. They are interested in: (i) an external truck parking area with a gate appointment system, (ii) advance information on truck arrivals, and (iii) round-the-clock use of AGVs. For further details on this case, we refer to Brunetti et al. (2020).

Our add-on enables us to evaluate dispatching and routing algorithms on a realistic network for the flow of freight. In this network, we can analyse the added value of autonomous vehicles and the use of advance information. Moreover, the network becomes a multimodal network thanks to our library of modes and locations. Ultimately, a synchromodal flow of freight could be generated with proper integration of cross-mode dispatching. To generate all 130 warehouses and terminals, the port authority provided us with names, centroid coordinates, and allowed modes for each location. Then, we manually placed (i.e., drag & drop) supply locations at highway exits, at the main water entrance, and at the railway connecting with the national rail system. The truck parking area is also manually placed. The resulting model is shown in Figure 6. The road network was generated in Plant Simulation 15.1 in 45 seconds with a high accuracy, resulting in 1,827 ways with 9,197 segments. Even though the area is way smaller compared to the first case, the numbers of ways and segments of the road network are slightly higher. This reflects the higher accuracy of the representation that includes service roads and detailed curvatures.

Similar to Case 1, we validate routes in the simulation model of Moerdijk using the OSRM. There are many supply and demand locations. Therefore, we study routes connecting some of the most popular locations. The routes connect the east and middle highway exits to the truck parking area, to a terminal, and to a warehouse (Figure 7). Results for travel distance and time are computed outside of peak hours and shown in Table 2. OSRM only provides distances in steps of 100 meters and travel times in steps of 30 seconds, thus lacking a proper level of detail to compare the results between OSRM and the add-on. The travel distance in our model is 0.2-1.2 % shorter than in the OSRM and the difference is always below

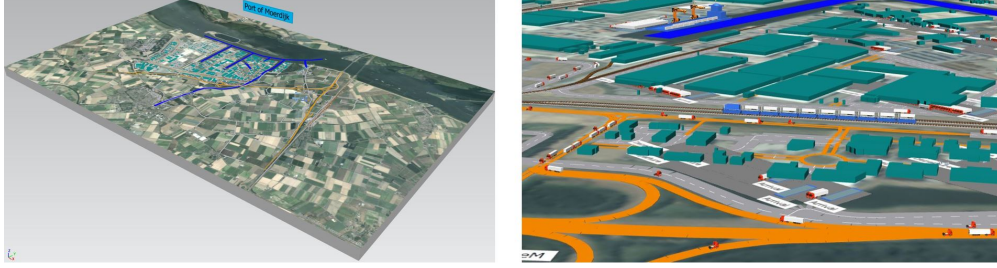


Figure 6: An overview (left) and traffic close-up (right) of the automatically generated simulation model of the Port of Moerdijk.

100 meters. In relative terms, the travel time differences are higher than in Case 1. This is caused by the fact that trips are much shorter; the absolute time difference for all routes is below 1 minute. Hence, we conclude that the add-on generates detailed models with negligible errors in travel distance and time.

Table 2: Validation of routes from two highway exits to logistics locations using OSRM and the add-on.

From east highway exit (1)	OSRM	Add-on	Δ (%)
To Truck Parking (3)	1.2 km / 1:30 m	1.19 km / 1:12 m	-0.8 % / -20 %
To Terminal (4)	5.8 km / 7:00 m	5.79 km / 7:07 m	-0.2 % / +1.7 %
To Warehouse 1 (5)	4.7 km / 8:00 m	4.69 km / 7:31 m	-0.2 % / -6.0 %
From middle highway exit (2)	OSRM	Add-on	Δ (%)
To Truck Parking (3)	3.4 km / 2:30 m	3.36 km / 2:45 m	-1.2 % / +10 %
To Terminal (4)	2.9 km / 4:30 m	2.89 km / 4:53 m	-0.3 % / +8.5 %
To Warehouse 1 (5)	3.6 km / 5:00 m	3.59 km / 5:41 m	-0.3 % / +13.7 %

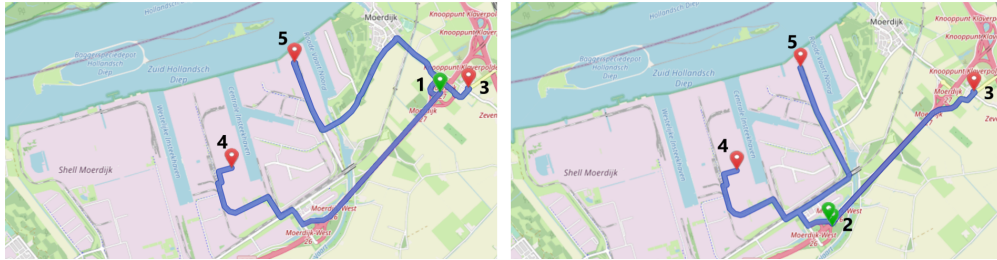


Figure 7: An overview of the six routes planned from two highway exits to the truck parking, to a terminal, and to a warehouse. Screenshot taken from the [OSRM web application](#).

5 CONCLUSIONS

In this paper, we presented a simulation add-on to automatically generate realistic multimodal logistics networks with OSM data in a simple and flexible way. The add-on is designed for general purpose discrete-event simulation software, to include elements of specialized traffic simulation software. This eases the implementation effort and increases the reliability of logistics simulation studies, e.g., to evaluate the benefits of new logistics concepts, such as autonomous vehicles, truck platooning, and synchronodal transport, but also to study possible disturbances in networks and resilient logistics. The networks include road, rail, and waterways as well as logistics locations such as warehouses, terminals, or people in need of relief goods. Next to the network generation approach, we presented various classes of transport modes to simulate multimodal and intermodal transport of freight. These classes are modeled with different levels of detail and vehicle behavior.

Further research will focus on congestion awareness and network disruptions when planning paths, for example with dynamic updates of the route weight attribute. Moreover, we plan to validate vehicle behavior and the emergence of congestion with real data collected at port or airport areas. Finally, future research can benefit from this simulation add-on due to reduced implementation effort and enabling the investigation of the use of advance information, considering stochastic or dynamic networks, or analysing integrated mode planning for synchromodal logistics.

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