

SIMULATION-OPTIMISATION BASED DECISION-SUPPORT FOR COORDINATED DISASTER RELIEF LAST-MILE DISTRIBUTION

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ABSTRACT

We present a simulation and optimisation based decision-support system to improve last-mile distribution of goods during disasters. In particular, the impact of road closures on supply and optimal transfer points is analysed by considering road, off-road and air transportation. To deal with panic buying, stockpiling and various consequences of a disaster over a rolling time-horizon, a limited number of transfer points have to be selected. At these points, relief organisations and retailers can transfer shipments to prevent stock-outs at regional stores. Furthermore, shipment requests are scheduled to vehicles, routed and optimised during each simulation run. Results show a significant reduction in average lead times when coordinating last-mile distribution during disasters.

Keywords: humanitarian logistics, agent-based simulation, last-mile distribution, decision support system

1. INTRODUCTION

Transportation highly impacts disaster relief operations (Berariu et al. 2015). Additionally, unexpected increases in demand during disasters are a huge challenge for private companies as well as relief organisations. Naohito et al. (2014) show a significant increase in household spending during the Great East Japan Earthquake of 2011; however, they also report that households were not able to stockpile goods to their desired levels. Holguín-Veras et al. (2014) note that demand also increased in areas not directly damaged by the disasters and that private companies were not able to sufficiently supply goods.

Enabling a robust and efficient supply chain benefits retailers, who are able to sell their goods, and relief organisations as panic is reduced if households are able to purchase the demanded goods. For instance, during Hurricane Katrina in 2005, Horwitz (2009) points out that the private sector was able to supply the affected area long before the public agencies arrived. Additionally, retailers often have a substantial amount of demand data available and the logistic experience to deal with disruptions in supply and demand. Public

agencies, in contrast, have the regulatory decision-making and special equipment to ship goods through affected areas.

To support combining these strengths, we introduce a decision-support system (DSS) to coordinate shipments between private and public actors. Therefore, we model road closures as well as road, off-road and air transportation. In particular, we focus on the situation where relief organisations perform shipments between transfer points in the affected areas. This is shown in Figure 1. In contrast to classical last-mile distribution where the relief organisation delivers goods directly to the victims, by coordinating these actions, resources are utilised efficiently and victims are potentially served faster and more consistently. Therefore, retailers perform the first and the last part of the shipment where roads are still intact, while relief organisations ship between two transfer points through the affected area.

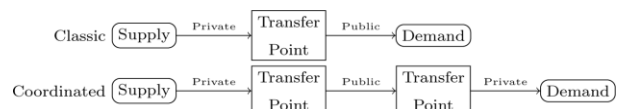


Figure 1: Disaster relief last-mile distribution

The DSS optimises routing and scheduling decisions, selects promising transfer points and allows analysing various disaster scenarios. Furthermore, users can interactively modify the analysed settings to test the impact of different policies. This enables improved decision-making and supports last-mile distribution. Consequently, the contribution of this paper is twofold, namely introducing a simulation-optimisation based DSS for disaster relief last-mile distribution and analysing the potential of coordinating shipments.

2. LITERATURE REVIEW

High computational times and a lack of integrated systems with the right complexity level are the main challenges in humanitarian logistic models (Özdamar and Ertem 2014). The selection of optimal transfer points in our work equals an uncapacitated facility location problem. It aims to find an optimal subset from potential candidate locations derived from an objective

function. For a survey on this topic, refer to Gao and Robinson Jr. (1994) and Verter (2011). Facility location in humanitarian relief is discussed by Balcik and Beamon (2008).

In disaster relief routing, optimisation can lead to major improvements; however, only little work is found (de la Torre et al. 2012). Routing full truckloads between transfer points can be classified as a full truckload pickup and delivery problem (FT-PDP) as introduced by Gronalt et al. (2003). Location-routing problems consider routing decisions when optimising facility locations. For recent surveys on this topic, refer to Prodhon and Prins (2014) and Drexl and Schneider (2015). Only few articles investigate stochastic problems and the impact of network disruptions is rarely analysed.

Longo and Ören (2008) note the importance of modelling and simulation to study supply chain vulnerability and to improve resilience. By combining simulation and optimisation, uncertainties and complex interactions within optimization models can be overcome (Glover et al. 1996). This allows one to investigate the impact of network disruptions as well as disasters on last-mile distribution and to further discuss the potential of coordination.

3. PROBLEM DESCRIPTION

In an area affected by a disaster, roads may be closed for certain durations of time during a day. Potential reasons for this are floods or road blockages as a result of earthquakes or mudslides. Due to panic buying and unexpected demand, stores randomly request additional shipments. Full truck-loads are assumed, i.e. no split-deliveries are performed and shipments have exactly one supply and one demand point. The private actor, e.g., a retailer, can either ship these directly or use the service of a public actor, e.g., a relief organisation. In the latter case, the retailer transports the goods to a transfer point. At this point, the relief organisation takes over the shipment through the affected areas to a second transfer point from where goods are delivered to the store by the retailer. To perform this service, the relief organisation has a number of given heterogeneous helicopters and off-road vehicles available which are dedicated for this purpose. Each is assigned to one of multiple depots where the vehicle starts and ends its operations. If idle, the vehicle always returns to the depot. Private trucks of the retailers are assumed to be always immediately available. While the retailer is only able to drive on open roads, the relief organisation can either fly or utilise closed roads due to special permissions and equipment. Relief organisations only perform shipments between predefined transfer points, where a limited number of facilities have to be selected from a large set of potential candidates. This selection has to be done before the first request occurs and cannot be altered later due to the high organisational effort of moving transshipment equipment. Transfer points can either be large parking areas, open fields or any other suitable area where transshipments can be performed.

All vehicles travel respecting speed limits on the individual arcs and are subject to loading and unloading times. The objective is to minimise the average lead time over all shipping requests, i.e. how long it takes on average to deliver shipments to stores from when the request occurred. Therefore, an optimal arrangement of transfer points, an optimal scheduling of requests to vehicles and optimal routes, all considering an uncertain environment and road closures, have to be derived.

Figure 2 gives a simple sample problem with only one request, four potential transfer points, one public vehicle, one depot, one supply point and one demand point. Due to the closure of a bridge, the retailer can perform a detour crossing the next bridge or coordinate the shipment with the relief organisation, which has an off-road vehicle available to cross the closed bridge. As the detour is substantial, the shipment is coordinated. Therefore, two transfer points have to be selected and the shipment has to be scheduled to the public vehicle. As a result, both vehicles travel to the first transfer point where the goods get transhipped. After arrival of the public vehicle at the second transfer point, the retailer delivers the goods to the store. The lead time is denoted by the difference between the arrival time at the store and the time when the request occurred.



Figure 2: Problem description

4. SIMULATION-OPTIMISATION BASED DSS

An agent-based simulation, a heuristic optimisation procedure to improve vehicle routes and a Tabu Search metaheuristic to select promising transfer points are combined to analyse the introduced problem. Inputs are demand and supply points, vehicle depots, potential transfer points as well as available vehicles, network data and information about road closures. The user specifies a number of requests and a time horizon in which these shipments occur. The simulation stops as soon as the last request is delivered and outputs lead times, vehicle routes and coordination decisions.

4.1. Agent-based Simulation

The agent-based simulation consists of four main components: locations, vehicles, requests and closed roads. Each is modelled as an agent in a geographic space based on the respective network data and coordinates. Locations further differ in stores, depots, transfer points and supply nodes. Vehicles indicate public vehicles, while private trucks are represented within the request agent. As dynamic changes in the simulation can lead to a high number of substantial rerouting and rescheduling decision, vehicles are defined with the statechart shown in Figure 3. If a request gets scheduled, the vehicle moves to the pickup location where it waits if it arrives before the private truck. While moving or waiting, the current task may be aborted to reroute the vehicle to serve a different shipment request. After a loading time delay the vehicle travels to the delivery location. During this trip, we assume that no rescheduling is possible as the vehicle is already loaded. As a result, splitting a shipment in multiple stages to be performed by different vehicles is not enabled. Finally, at arrival at the delivery location, the shipment is transferred to the private truck and the public vehicle continues with its next scheduled request. If no further requests are scheduled, the vehicle returns to the depot.

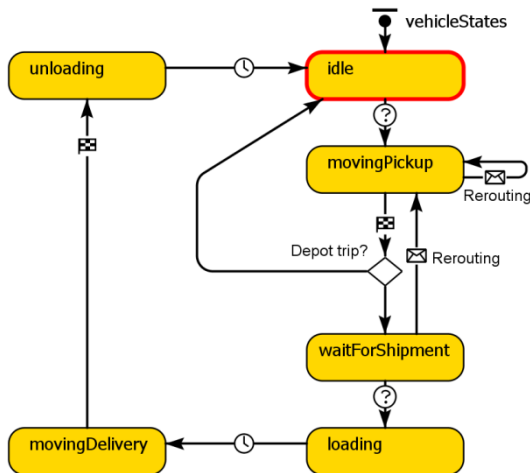


Figure 3: Statechart of public vehicles

The given number of requests are uniformly randomly distributed over time and associated to randomly selected supply points and stores. To calculate the shortest path on the street network between two locations, a bidirectional implementation of the A* algorithm (Hart et al. 1968) is used. Helicopters are assumed to fly in a straight line; however, adding a special routing graph for this purpose is possible. Closed roads are specified as input and associated with a start and end time. The cost of traversing closed roads with private vehicles is set to infinity, forcing the routing algorithm to look for alternative paths.

4.2. Coordination Decision

Each time a new request occurs or roads open or close, the solution procedure has to decide if a transshipment should be performed. If so, it decides at which transfer points and which public vehicle should at what time bridge the affected area. Figure 4 gives a simplified example of a decision if a transshipment should be performed considering loading and unloading times of 10 minutes. Due to a road closure, the direct delivery between supply point S_1 and store D_1 is not possible. As a consequence, the retailer can either select a detour or request a transshipment via transfer point T_1 and T_2 with a relief organisation. Due to loading times, the detour is faster, which results in no transshipment in this case.

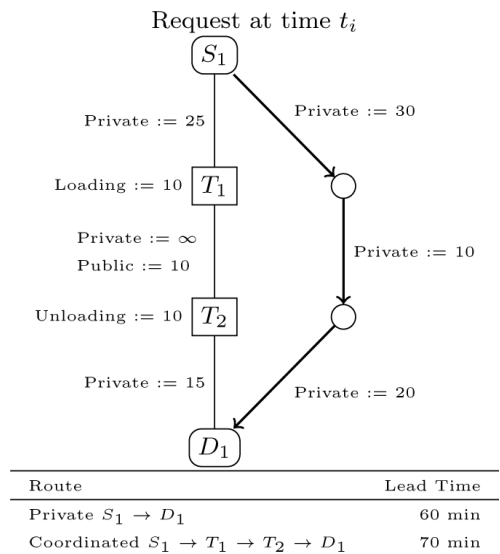


Figure 4: Routing and transshipment decision

If coordinating is potentially beneficial, where to load and unload this request on a public vehicle has to be decided. Therefore, a cheapest insertion heuristic tests all promising transfer combinations on each position within each vehicle's schedule. One option is to select transfer points, which result in the shortest total travel duration, i.e. the shipment travels on the shortest path; however, depending on the current availability of public vehicles this potentially results in substantial wait times. Depending on which vehicle arrives later, either the shipment or the public vehicle waits. As a consequence, wait times are considered by selecting transfer points individually for each vehicle within the routing and scheduling algorithm. Therefore, all combinations of loading and unloading points where the shortest path is less than the best found combination so far for this request are evaluated. Figure 5 gives a simplified example ignoring loading and unloading times. Vehicle V_1 first finishes its current shipment to transfer point T_3 and then continues to T_1 . This trip requires 20 minutes. The private truck arrives after 15 minutes, resulting in 5 minutes of wait time for the request. After the loading operations, the request continues to the demand point with transshipment at T_2 . The request arrives at the final location after 35 minutes. This value is compared to the

best found combination for the request so far and updated if improved. Changes in the route of the public vehicle can, however, lead to delays for other requests scheduled after the inserted change. These costs have to be additionally considered to evaluate transshipments.

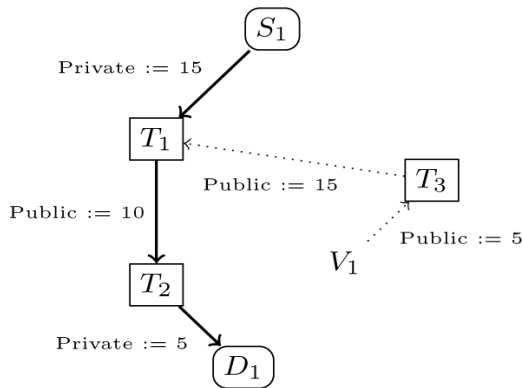


Figure 5: Lead time calculation to select transfer points

The best combination is selected and scheduled. Whenever a road is closed or reopened, all previously made decisions are re-evaluated and improved if possible. To speed up computation, non-promising combinations are aborted if already worse than the best found combination so far. In the next step, the routing of the vehicle is optimised.

4.3. Trip Assignment and Improvement

Each time after a request is scheduled or re-scheduled an intra-route optimisation operator aims to improve the schedule where the request is inserted. Therefore, swapping the order of two requests on this vehicle is tested. Additionally, an inter-route relocate operator checks if moving a request from one vehicle to another improves the objective value. Both operators follow a best improvement strategy, i.e. all potential improvements are tested and the best is applied. This is repeated until no further improvements are found.

The occurrence of new shipments can, however, lead to a situation where it is advantageous to cancel earlier made coordination decisions as it beneficial to utilise public vehicles for other requests instead. To consider this fact, a drop operator is implemented and run after inter-route optimisation. It checks if removing a request from a public vehicle and delivering it directly with a private truck from its current position reduces the average lead time over all requests. Therefore, only public vehicles which were changed during the inter-route optimisation or as a result of an insertion of new requests are evaluated to reduce computational time. In case a request is dropped from a vehicle, the inter-route optimisation procedure is restarted.

4.4. Selection of Transfer Points

As equipment to perform transshipment is limited and further time-consuming to relocate during disasters, the decision-makers may only be able to operate a limited number of transfer points. Selecting a good set of transfer points allows reducing lead times and

improving the system's performance. Nevertheless, this decision is not trivial due to network disruption and unknown demand. As a consequence, a Tabu Search (Glover 1989; Glover 1990) was implemented to select a limited number of transfer points out of a set potential candidate locations. Tabu Searches show promising results for multiple related optimisation problems such as the uncapacitated facility location problem (Ghosh 2003), the p-median problem (Rolland et al. 1997) and locating emergency facilities under random network damages (Salman and Yücel 2015). Each candidate location is associated with a binary variable y_i , which equals 1 if open and 0 if closed.

To generate an initial solution, a construction heuristic was developed which selects transfer points based on their attractiveness for transshipments. Therefore, the simulation is run for a pre-specified number of replications runs with all potential candidate transfer points being open and collects statistics about how often a shipment was loaded or unloaded at a certain candidate. In the next step, these candidates are sorted and the most utilised transfer points are added to the initial solution until the maximum number of transfer points is reached.

The initial solution is further improved in the following iterations by a swap operator which opens one transfer point by simultaneously closing a previously open one. Each potential solution in this neighbourhood is evaluated by running the specified number of replication runs of the simulation. The best solution of the iteration is stored and acts as the incumbent solution for following iteration. The selected move is set tabu for τ iterations, i.e. it is not allowed to be undone. Nevertheless, if performing this move improves the overall best found solution so far, the tabu criteria is revoked. Furthermore, moves which lead to a worse objective value compared to the last iteration are penalised based on how often the respective candidate has been added to the solution in prior iterations. This helps to diversify the search procedure and is done by the following evaluation function $g(S)$ with $f(S)$ indicating the objective value of the solution, k_i the times a transfer point has been previously added to a solution and ζ the penalty weight.

$$g(S) = f(S)(1 + \zeta k_i) \quad (1)$$

After either a given time limit or a maximum number of iterations, the Tabu Search terminates and returns the best found objective value as well as the best set of transfer points to operate.

4.5. Dynamic extensions

The simulation further allows including sudden car breakage as well as changes in air weather, which enables or disables air transportation. Furthermore, roads and transfer points may be closed or open dynamically based on pre-specified stochastic distributions or by user interaction. In each of the cases, all affected requests are re-evaluated if transshipment

should be adjusted considering the new situation. Allowing the user to dynamically perform such changes during a simulation run enables one to test different scenarios, run risk assessments and to visualise potential impacts.

5. COMPUTATIONAL EXPERIMENTS

The DSS is developed with AnyLogic 7.1 (AnyLogic 2015) using OpenStreetMap (OpenStreetMap 2015) and a custom implementation of GraphHopper 0.3 (GraphHopper 2015) to route vehicles on different networks. The solution procedure is coded in Java. Computational experiments were run on an Intel Core i7-4930K, 64GB RAM, MS-Windows 7 and 6 threads operating in parallel.

5.1. Test Scenario

Test area is Krems an der Donau, Austria, and the surrounding area, a region often affected by floodings of the Danube River Basin. To reach the city center of Krems, shipments either have to cross the Danube River on one of two bridges or circumvent the area to take a major highway bridge in the east of the region. As demand points, the geographic position of supermarkets, pharmacies and other major retailers in the area are selected. These stores are supplied from two supply points in the east, one north of the Danube and one south, both located at highway exits. To indicate potential transfer points, large parking lots as well as football pitches and industrial areas were selected. Therefore, it is assumed that all transfer points are accessible for both air and off-road vehicles. In total, 29 stores, two supply points and 80 potential transfer points are available. Figure 6 plots the studied region.

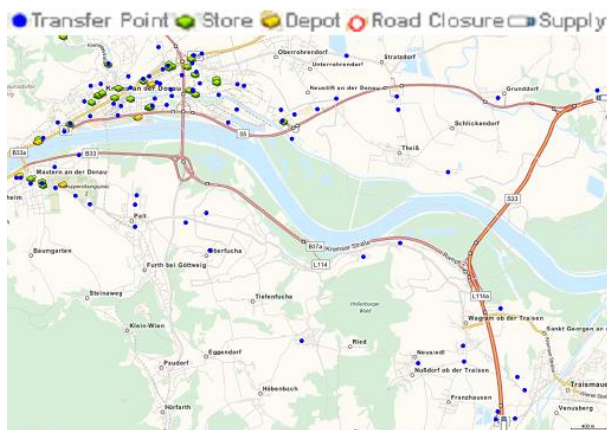


Figure 6: Test scenario area

Two helicopters and three off-road vehicles are stationed at five depots in the region. Vehicle depots were located based on fire-fighter stations in the area, a military barrack and a major hospital. Helicopters travel with an average speed of 135 km/h and require six minutes for loading and unloading operations. Off-road vehicles travel with 45 km/h and take three minutes for loading operations. Private trucks travel respecting individual speed limits of each road with a maximum

travel speed of 95 km/h. Road closures are set as reported by the Austrian Press Agency (APA-OTS 2013) for the 7th of June, 2013 when the region was struck by a major river flooding. Roads are closed for the entire period and travel times are considered to be certain, e.g., there is no random component in the time it takes to travel between two points. Based on opening hours of stores in the region, the simulation starts at 8am and shipment request may occur until 4pm. The average number of shipment requests per store in the computational experiments is varied between one and fifty requests over the eight hours simulation horizon. Furthermore, all dynamic extensions reported in Section 4.5 are disabled for the computational experiments to enable clearer comparisons of different policies by reducing stochastic impacts.

5.2. Parameter Setting

To consider stochastic effects in demand, each evaluation is run with 100 replications and average results are reported in this work. The initial solution is constructed based on the attractiveness of transfer points after 6 runs. For the optimisation of facility locations, the tabu tenure τ is uniformly randomly selected after each iteration in $[0, \lceil \sqrt{n} \rceil]$ with n indicating the number of potential candidate facilities. The diversification penalty ζ is randomly set in $[0, 0.1]$ after each iteration to vary diversification. The time limit is set to 30 minutes. To speed up optimisation, replications are aborted for a single solution if the current mean is worse than the best found solution in the current iteration based on a confidence level of 95% and after a minimum of 6 replications. Additionally, memory techniques are used to store reoccurring evaluations, solutions are evaluated in parallel on multiple threads of the computer systems and all visual animations are disabled.

5.3. Preliminary Results and Discussion

Figure 7 shows a solution with three transfer points to open and with on average five shipments requests occurring per store during the simulation horizon. Due to the road closures, two main connections within the city of Krems as well as one of the two bridges are not traversable for private vehicles. As a consequence, out of the 80 potential candidate locations, the Tabu Search selects three candidate locations for the coordination with the objective to reduce average lead times.

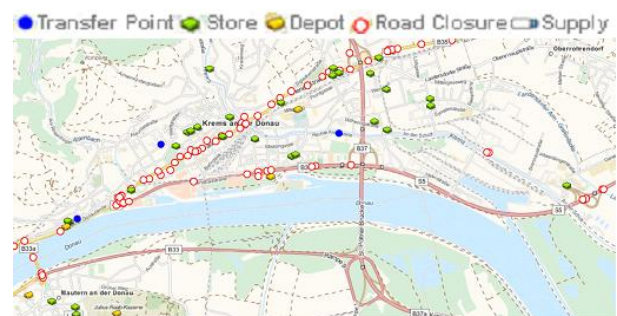


Figure 7: Sample solution for the 07th June 2013.

Two transfer points are located closely to stores where direct connections are disrupted by road closures. The third one is located closely to the exit of the main bridge entering the area. At this point, the public actor takes over the shipment to bridge the affected area to one of the other two transfer points.

5.3.1. Impact of Coordination

To analyse the impact of coordinating last mile distribution, three settings are compared. Therefore, the three prior selected transfer points are used. “Best case” indicates the situation where no roads are closed. It gives a natural lower bound for the system performance. Note that, due to a higher travelling speed and different routes of helicopters, coordination can potentially lead to a lower average lead time if no roads are closed; however, it can be assumed that no coordination between public and private actors is performed in such a setting. “Worst case”, in contrast, indicates the situation where no public vehicles are used and private trucks use the remaining open roads to deliver goods to stores. This setting acts as a natural upper bound. Both can be, assuming a uniform distribution of supply and demand points of requests and no changes in the street network, calculated by determining the average lead time $\mu_{c_{ij}}$ from all s supply points to all m stores under the given street network.

$$\mu_{c_{ij}} = \frac{1}{sm} \sum_{i=1}^s \sum_{j=1}^m c_{ij} \quad (2)$$

“Coordinated” allows transshipments of goods as studied in this paper and requires one to run the solution produce. Figure 8 plots the benefits of providing public vehicles to transfer goods through the affected areas.

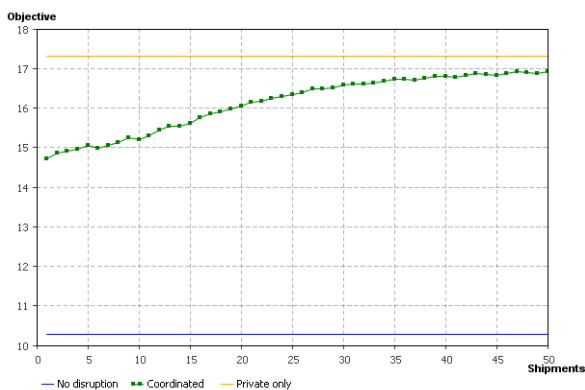


Figure 8: Impact of disaster-relief coordination

Compared to the worst case scenario, average lead times are substantially reduced, especially if only few shipments occur. In this case, public vehicles are only little utilised and can efficiently transfer shipments. Nevertheless, the optimal scenario where no road closures occur is not reached due to detours to transfer points, additional loading times, waiting times for vehicles and varying travelling speeds of different vehicles. In general, the number of available public

vehicles and the extend of road closures, as well as travelling speed of public vehicles and loading and unloading times have a major impact on the benefits of last-mile coordination in disaster relief.

If the number of shipments per store increases, utilisation rises as well and, as a consequence, substantial wait times occur. High wait times further lead to more cases where a detour is faster compared to coordinating the shipment. As a result, with a higher number of shipments, average lead times converge to the worst case lead time without coordination as only few gains can be realised. In such a setting, adding more vehicles for the coordination is beneficial.

5.3.2. Impact of Vehicle Optimisation

Optimisation within a dynamic setting is challenging as decisions which are “optimal” considering the current status of the problem might lead to negative effects later when the problem changes due to the occurrence of new requests. To analyse the impact of our optimisation procedure, it is compared to a simple scheduling rule, which adds a new shipment to the end of the vehicle schedule which results in the lowest average lead time. Nevertheless, all potential combinations of transfer points are evaluated in this step. Furthermore, no inter- and intra-route changes are performed. Results of both methods are compared in Figure 9 with the three prior selected transfer points.

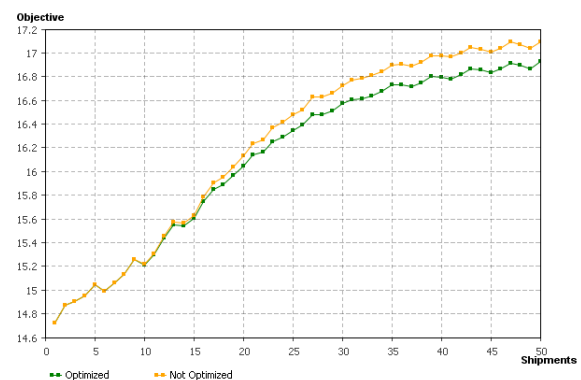


Figure 9: Impact of the optimisation procedure

The analysis shows that given a small number of shipments per store, the optimisation procedure has nearly no impact. The main reason for this is the low number of shipments simultaneously scheduled to a single vehicle. This gives little room for improvement. With an increasing number of shipments, however, the number of simultaneously scheduled requests per vehicle increases, allowing the optimisation procedure to improve average lead times by altering vehicle routes. Based on these results, the user is given the option to deactivate the optimisation procedure prior to a simulation run to save on computational run time.

5.3.3. Impact of Number of Transfer Points

Opening more transfer points increases organisational efforts and potentially costs; however, average lead

times are expected to decrease as better coordination can be achieved. To plot the impact of the number of transfer points, the optimisation was run for each potential number of transfer points to open with 5 shipments requests per store. Results of this analysis are shown in Figure 10.

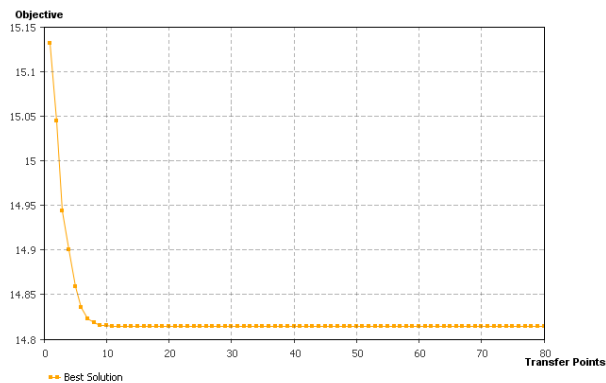


Figure 10: Impact of the number of open transfer points

As expected, average lead times are the highest if only a few transfer points are operated. Adding an additional transfer point decreases the lead time substantially if only few facilities are open, while little to no impact is achieved if many candidates are already selected. Furthermore, after 13 facilities, opening an additional transfer point is no longer beneficial as the additional facility is not utilised for transshipments and, as a consequence, does not improve the system's performance. Analysing the problem in this way, helps to reduce the problem size substantially as non-promising candidates can be removed from the set of potential facilities to improve run times. Additionally, having fewer candidates to consider allows decision-makers to closer investigate the remaining candidates.

6. CONCLUSION

To support coordinated last-mile distribution during disasters, DSSs are crucial to investigate and analyse potential strategies and resulting trade-offs. The introduced DSS offers this by combining simulation and optimisation techniques. The focus on modelling real-world transportation networks and the consideration of road closures enables one to utilise the developed tool in education and training activities. It helps to define promising locations of transfer points, analyse the impact of road closures and further plots the benefits of coordination. As a result, future decision-making in the context of disaster relief logistics can be improved to support victims effectively and to lower the impact of disasters.

Future work includes facilitating the developed DSS to test the impact of certain road closure on the performance of the system. Additionally, embedding the DSS in the development of serious games to train decision-makers is one potential research direction of high interest.

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REFERENCES

- AnyLogic, 2015. AnyLogic - Multimethod Simulation Software. Available from: <http://www.anylogic.com/> [accessed 25 June 2015]
- APA-OTS, 2013. Aktuelle Straßensperren wegen Hochwassers in Niederösterreich. Available from: http://www.ots.at/presseaussendung/OTS_201306_07_OTS0088/aktuelle-strassensperren-wegen-hochwassers-in-niederosterreich [accessed 25 June 2015]
- Balcik, B., Beamon, B. M., 2008. Facility location in humanitarian relief. *International Journal of Logistics*, 11(2), 101-121.
- Berariu, R., Fikar, C., Gronalt, M., Hirsch, P., 2015. Understanding the impact of cascade effects of natural disasters on disaster relief operations. *International Journal of Disaster Risk Reduction* 12, 350-356.
- de la Torre, L. E., Dolinskaya, I. S., Smilowitz, K. R., 2012. Disaster relief routing: Integrating research and practice. *Socio-Economic Planning Sciences* 46 (1), 88-97.
- Drexl, M., Schneider, M., 2015. A survey of variants and extensions of the location-routing problem. *European Journal of Operational Research* 241 (2), 283-308.
- Gao, L.-L., Robinson Jr., E., 1994. Uncapacitated facility location: General solution procedure and computational experience. *European Journal of Operational Research* (3), 410-427.
- Glover, F., Kelly, J. P., Laguna, M., 1996. New advances and applications of combining simulation and optimization. In: *Proceedings of the 28th Conference on Winter Simulation. WSC '96*. IEEE Computer Society, Washington, DC, USA, pp. 144-152.
- Ghosh, D., 2003. Neighborhood search heuristics for the uncapacitated facility location problem. *European Journal of Operational Research* 150 (1), 150-162.
- GraphHopper, 2015. Graphhopper route planner. Available from: <https://graphhopper.com> [accessed 25 June 2015]
- Gronalt, M., Hartl, R. F., Reimann, M., 2003. New savings based algorithms for time constrained pickup and delivery of full truckloads. *European Journal of Operational Research* 151 (3), 520-535.
- Hart, P., Nilsson, N., Raphael, B., 1968. A formal basis for the heuristic determination of minimum cost paths. *Systems Science and Cybernetics, IEEE Transactions on* 4 (2), 100-107.

- Holguín-Veras, J., Taniguchi, E., Jaller, M., Aros-Vera, F., Ferreira, F., Thompson, R. G., 2014. The Tohoku disasters: Chief lessons concerning the post disaster humanitarian logistics response and policy implications. *Transportation Research Part A: Policy and Practice* 69, 86-104.
- Horwitz, S., 2009. Wal-Mart to the rescue: private enterprises response to Hurricane Katrina. *The Independent Review* 13 (4), 511-528.
- Longo, F., Ören, T., 2008. Supply chain vulnerability and resilience: a state of the art overview. *Proceedings of European Modeling & Simulation Symposium*, pp. 527-533. 17-19 September 2008, Campora S. Giovanni (CS) Italy.
- Naohito, A., Moriguchi, C., Noriko, I., 2014. The effects of natural disasters on prices and purchasing behaviors: The case of the Great East Japan Earthquake. *RCESR Discussion Paper Series DP14-1*, Research Center for Economic and Social Risks, Institute of Economic Research, Hitotsubashi University.
- OpenStreetMap, 2015. OpenStreetMap. Available from: www.openstreetmap.org [accessed 25 June 2015]
- Özdamar, L., Ertem, M. A., 2014. Models, solutions and enabling technologies in humanitarian logistics. *European Journal of Operational Research* 244 (1), 55-65.
- Prodhon, C., Prins, C., 2014. A survey of recent research on location-routing problems. *European Journal of Operational Research* 238 (1), 1-17.
- Rolland, E., Schilling, D. A., Current, J. R., 1997. An efficient tabu search procedure for the p-median problem. *European Journal of Operational Research* 96 (2), 329-342.
- Salman, F. S., Yücel, E., 2015. Emergency facility location under random network damage: Insights from the Istanbul case. *Computers & Operations Research* 62, 266–281.
- Verter, V., 2011. Uncapacitated and capacitated facility location problems. In: Eiselt, H. A., Marianov, V. (Eds.), *Foundations of Location Analysis*. Vol. 155 of *International Series in Operations Research & Management Science*. Springer US, pp. 25-37.

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