ASSESSMENT OF SELF-ORGANIZING RAILWAY OPERATIONS AND RECOMMENDATIONS

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Following project partners have been involved in the elaboration of this document:

Partner No.	Company short name	Involved experts
1	univEiffel	Grégory Marlière, Federico Naldini, Bianca Pascariu, Paola Pellegrini
2	SNCF	Rémy Chevrier

3	DTU	
4	BDK	
5	ISTC-CNR	Leo D’Amato, Fabio Oddi, Vito Trianni
6	RFI	
7	TUDelft	Egidio Quaglietta, Kemal Keskin, Konstantinos Rigos

Executive Summary

This deliverable illustrates final outcomes of the SORTEDMOBILITY project. Validation and assessment of developed algorithms are reported together with a potential analysis of self-organising rail traffic management. The validation of the data-driven demand forecast model shows that for a portion of the Copenhagen rail network, accurate predictions of observed demand trends can be achieved. The impact of the developed self-organising rail traffic management algorithms is assessed by applying the SORTEDMOBILITY simulation platform (illustrated in Deliverable D4.2) to the three case studies: the single-track line Guingamp-Paimpol, the urban Copenhagen network and the mixed-traffic line Pioltello-Rovato. Self-organising traffic management has been compared to the centralised approach for several delay scenarios in terms of total train delays, delay costs and total passenger travel times. Both approaches are benchmarked versus the baseline case considering trains to follow the timetabled train passage order at stations/junctions. Simulation experiments show that self-organising and centralised traffic management significantly reduce train delay propagation versus the timetabled train order while generally achieving very similar train lateness performances. With respect to passenger travel times, self-organisation outperforms the centralised approach in certain cases. However, in conditions of high-density traffic (such as the Copenhagen case) and longer dwell times, the relative benefit of self-organisation on passenger travel times decreases due to the limited local traffic view, whose effect is more relevant in dense traffic. A multi-target Delphi analysis is then illustrated which identifies potentials of rail traffic self-organisation versus strategic transport sustainability targets. Self-organisation is recognised as an opportunity to remove current hurdles to multi-modal transport integration by: i)accelerating rail digitalisation, ii) fostering policies/techs for data sharing, iii) integrating information on passengers and other transport modes in rail traffic management. Recommendations enabling such a paradigm shift include quantitative cost/benefit analyses, a progressive rail digitalisation process and joint stakeholder actions to transition to a cooperative, open-data rail system.

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1 INTRODUCTION

SORTEDMOBILITY project explores the potential of self-organizing railway traffic management to address current limitations in centralized rail systems. Computational complexity of traditional centralized traffic management approaches can indeed increase exponentially for large and/or dense-traffic rail networks, hence not practically applicable in those cases. Self-organizing systems, on the other hand, allow individual trains to autonomously identify and mutually negotiate local rescheduling decisions which consider individual priorities and real-time conditions. Given the local nature of the decisional processes computational efficiency can be increased, thereby improving scalability, flexibility and responsiveness of traffic management to tackle unforeseen traffic perturbations.

The research described in this deliverable has the objective of validating and assessing the algorithms for travel demand estimation and self-organising rail-traffic management developed in the SORTEDMOBILITY project. In addition, a potential analysis is presented which identifies existing gaps in current traffic management and advantages that rail traffic self-organisation can provide to fast-forward the achievement of the EU White Paper's goals on transport sustainability. A set of recommendation is then reported to enable migration to a self-organising rail traffic paradigm.

First, a validation of the data-driven demand prediction models (illustrated in Deliverable D2.2) has been made based on observed demand trends collected for a portion of the Copenhagen rail network. Successively, an impact assessment of the developed self-organising rail traffic management algorithms (described in Deliverable D3.2) has been performed by means of the integrated SORTEDMOBILITY simulation platform (described in Deliverable D4.2). The assessment refers to the three considered case studies the single-track rural line Guingamp-Paimpol, the dense-traffic urban network in Copenhagen and the mixed-traffic line Pioltello-Rovato. Self-organising traffic management is compared versus a traditional centralised approach in terms of train delays and passenger travel times. Both traffic management approaches are benchmarked against the baseline which refers to timetabled train passage orders at stations/junctions. A multi-target Delphi analysis is then described which collects expert opinions to identify current gaps in rail traffic management, as well as potentials and recommendations for self-organising rail traffic to achieve strategic transport sustainability targets.

The deliverable provides in Section 2 the validation of the data-driven demand prediction algorithms. Section 3 describes results from the simulation-based impact assessment of self-organising traffic management algorithms for the three case studies. Sections 4 illustrates the expert-based potential analysis of self-organising rail traffic management and a set of recommendations for enabling a traffic paradigm shift. Conclusions are instead reported in Section 5.

2 INTEGRATED ASSESSMENT OF MODELS AND ALGORITHMS

2.1 Demand Prediction Validation

The Validation of the Data-Driven Operational Prediction Model presented in D2.2 was performed in two dimensions: scalability and robustness. For the scalability dimension, we test our proposed model on three different graph scales of the railway network, including the 12 ODs case, the "Tiny Copenhagen" case, and the "Full Copenhagen" case. In the 12 ODs case, we select the 12 OD pairs with the highest average demand. The "Tiny Copenhagen" case encompasses 12 contiguous stations in the network, resulting in 132 OD pairs, while the "Full Copenhagen" case covers the entire railway network with 84 stations, resulting in 6972 OD pairs (see Figure 1).

The OD-demand dataset used in both training and testing the model is constructed based on the Danish nationwide AFC system called "Rejsekort," a smart card where users tap in (origin) and tap out (destination) of the system, which are recorded. We collected the demand information over the whole 84 stations in the railway network over an 11-month period from January 29, 2021, to December 3, 2021. Data was collected only 5 days per week during peak periods from 5 AM to 12 PM. For the training and test set split, we randomly chose 60 days within the 11-month period as test data while the remaining days served as training data.

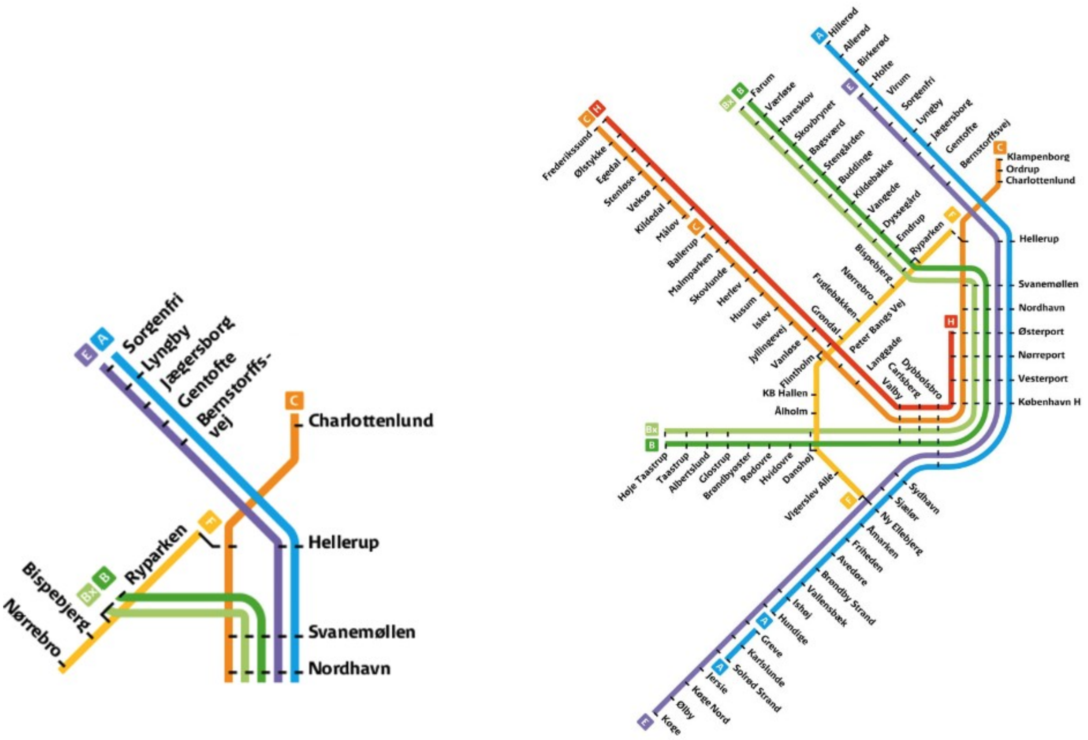
We note that this AFC data set does not account for all demand in the network, it does represent the main demand patterns on the Danish public transportation network. Future work is required to include additional data to scale up the current framework to the total demand.

For validation, we employ different prediction methods as follows:

- RR: Ridge Regression is a type of linear regression that includes a regularization term to prevent overfitting, especially when dealing with multicollinearity or when the number of predictors is larger than the number of observations (Rodrigues, 2023). The regularization parameter λ is tuned from 1e-3 to 1e-7, with the optimal value being 1e-6.
- XGB: XGBoost is an advanced implementation of gradient-boosted decision trees designed to be highly efficient, flexible, and portable (Chen et al., 2016). XGBoost provides a significant improvement over traditional gradient-boosting algorithms for different classification and regression

predictive modelling problems. The learning rate is tuned among 0.1, 0.01, and 0.001, while the maximum depth of the tree is tuned to 2, 4, and 6. For the 12 ODs case, the optimal learning rate is 0.1, while for the tiny and full Copenhagen cases, the optimal learning rate is 0.001. The best parameter for maximum depth is 6.

- GCN: Graph Convolutional Neural Network is a graph representation learning method that serves as the foundation for many OD prediction models. Our GCN model contains two layers with 64 hidden units and a learning rate of 1e-4. GCN extends the concepts of convolutional neural networks (CNN) to graph-structured data.
- NRI-GNN: Neural Relational Inference GNN model is a state-of-the-art prediction model based on GNN (Tygesen et al., 2023). In NRI-GNN, the graph adjacency matrix is learned by the encoder based on the NRI method (Kipf et al., 2018), while the decoder is a Gated Recurrent Unit (GRU) that takes the features and the dynamic graph generated by the encoder as input and outputs the predicted demand at time t + 1 for all nodes. In our experiment, NRI-GNN is used as a baseline to evaluate the performance of the proposed method on the 12 ODs case and the Tiny Copenhagen case, and was the model proposed in D2.2. For the Full Copenhagen case, NRI-GNN runs out of memory and is not scalable.
- Finally, we have also developed an enhanced architecture called mGraphSAGE (Multi-Graph Inductive Representation Learning) able to scale to the Full Copenhagen case, which was not modelled in deliverable D2.2. The technical details of this method are presented in the following scientific publication (Nguyen et al. 2024):



(a) Tiny Copenhagen case (b) Full Copenhagen case

Figure 1. URT line maps of real-world S-train case studies

We evaluate the prediction error of all models using two metrics: RMSE (Root Mean Square Error) and MAE (Mean Absolute Error). However, evaluating the model under different scales and different reliability-related states of the system helps to understand the specific characteristics of the prediction model that are appropriate for dealing with real-world prediction tasks, beyond just focusing on prediction accuracy. Thus, we also test the prediction model by selecting periods when unexpected events occur in the URT system, such as cancellations or delays. More specifically, the different prediction periods for model robustness evaluation are as follows:

- Periods with an average number of train cancellations at the origin/destination station in the last hour greater than 0.
- Periods with an average train delay time at the origin/destination station in the last hour greater than 60, 180 and 300 seconds.

Finally, all the models are implemented with PyTorch on a desktop computer with an AMD42 Ryzen Threadripper 3960X 3.8GHz CPU, 128 GB of RAM, and an NVIDIA GeForce RTX 308043 Ti GPU.

2.2 Results

The average prediction error for baseline methods compared to mGraphSAGE across the 12 ODs, Tiny Copenhagen, and Full Copenhagen cases is presented in Tables 1, 2, and 3. Training times for mGraphSAGE are 1 hour, 5 hours, and 48 hours for these three network scales, respectively. We also consider the prediction error in different scenarios involving uncertainties in the URT system, as previously described.

Table 1. Results for the 12 ODs case

Methods	RR		XGB		GCN		NRI-GNN		mGraphSAGE	
Metrics	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE
All periods	3.23	2.12	3.18	2.1	3.25	2.15	1.72	1.13	3.19	2.1
Cancelations at origin >0	3.46	2.56	3.37	2.52	3.48	2.6	2.45	1.65	3.37	2.52
Cancelations at destination >0	3.38	2.48	3.28	2.43	3.39	2.51	2.45	1.67	3.29	2.44
Mean delays at origin >60s	3.07	2.09	3.02	2.06	3.12	2.14	1.79	1.15	3.03	2.07
Mean delays at origin >180s	2.29	1.85	2.27	1.84	2.37	1.93	1.92	1.35	2.31	1.87
Mean delays at origin >300s	2.21	1.8	2.12	1.74	2.25	1.85	1.47	1.24	2.2	1.8
Mean delays at destination >60s	2.93	1.98	2.87	1.98	2.94	2	1.7	1.13	2.9	1.95
Mean delays at destination >180s	2.18	1.71	2.15	1.69	2.25	1.76	1.79	1.26	2.2	1.71
Mean delays at destination >300s	2.15	1.83	2.04	1.75	2.19	1.89	1.22	1.07	2.15	1.85

Table 2. Results for the tiny Copenhagen case

Methods	RR		XGB		GCN		NRI-GNN		mGraphSAGE	
Metrics	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE	RMSE	MAE
All periods	0.712	0.439	0.712	0.438	0.700	0.427	1.031	0.580	0.688	0.426
Cancelations at origin >0	0.737	0.499	0.735	0.497	0.728	0.486	1.071	0.658	0.718	0.484
Cancelations at destination >0	0.701	0.486	0.704	0.487	0.696	0.476	1.004	0.636	0.683	0.474
Mean delays at origin >60s	0.727	0.466	0.732	0.469	0.716	0.454	1.020	0.606	0.700	0.450
Mean delays at origin >180s	0.713	0.468	0.722	0.471	0.702	0.454	1.022	0.617	0.687	0.453
Mean delays at origin >300s	0.796	0.530	0.805	0.528	0.785	0.511	1.132	0.693	0.771	0.514
Mean delays at destination >60s	0.751	0.484	0.760	0.488	0.743	0.476	1.003	0.605	0.723	0.468
Mean delays at destination >180s	0.767	0.502	0.775	0.507	0.751	0.489	1.043	0.658	0.737	0.490
Mean delays at destination >300s	0.767	0.528	0.772	0.528	0.750	0.512	1.031	0.684	0.737	0.516

Table 3. Results for the full Copenhagen case

Methods	RR		XGB		mGraphSAGE	
Metrics	RMSE	MAE	RMSE	MAE	RMSE	MAE
All periods	0.345	0.186	0.338	0.182	0.332	0.181
Cancelations at origin >0	0.257	0.18	0.256	0.180	0.247	0.173
Cancelations at destination >0	0.256	0.177	0.254	0.177	0.246	0.17
Mean delays at origin >60s	0.255	0.163	0.250	0.160	0.246	0.158
Mean delays at origin >180s	0.198	0.157	0.199	0.159	0.194	0.154
Mean delays at origin >300s	0.23	0.187	0.227	0.183	0.221	0.178
Mean delays at destination >60s	0.239	0.158	0.234	0.155	0.237	0.159
Mean delays at destination >180s	0.321	0.238	0.326	0.242	0.316	0.236
Mean delays at destination >300s	0.479	0.376	0.484	0.380	0.471	0.37

Our results show that classic models turn out to be competitive with the complex and computationally-demanding graph-learning-based approaches proposed, especially as the studied network (and associated data) becomes larger. Yet, informative graphs can still help in tackling the need for capturing the dependencies in the data in many situations, especially spatial and temporal correlations often affected by operations.

3 IMPACT ASSESSMENT OF SELF-ORGANIZING RAIL OPERATIONS

In this section, we report the set-up and the results of the experimental analysis we propose for assessing the performance of self-organizing traffic management. The algorithms considered are the ones described in D3.2 - Algorithms for Self-Organizing Railway Operations (SORTEDMOBILITY Deliverable 3.2, 2023). The results obtained by self-organizing traffic are compared to the ones achieved by RECIFE-MILP, a state-of-the-art approach for centralized traffic management (Pellegrini et al., 2015). Moreover, we consider the timetable order as a reference. This is the traffic evolution if no decision is made to change the plan with respect to the timetable: the routes are the timetable ones for all trains, and the passing orders are those that were originally planned, in disregard of possible train delays. In the comparison of traffic management performance, we consider the timetable order as our reference, and we compute KPIs obtained by RECIFE-MILP and self-organization as a percentage with respect to it. For example, if self-organization implies a traffic evolution bringing to a total train delay of 10 minutes while the timetable order implies a total train delay of 20 minutes in the same perturbation scenario, we will say that timetable order has a delay of 100% and self-organization of 50%.

The experiments are operated in closed-loop: the simulator represents reality. It periodically shares traffic details (train positions and expected perturbations) and it implements the decisions made by the traffic management system on train route, passing orders and connections to be preserved. This closed loop is detailed in D4.2 - Integrated Platform for Assessing Self-Organizing Railway Operations (SORTEDMOBILITY Deliverable 4.2, 2023). It requires the definition of two parameters, the re-optimization period and the traffic state horizon. The former indicates every how many minutes information is shared by the simulator, and hence how often traffic management decisions are re-assessed. The latter defines how far into the future the traffic situation is predicted in order to make decisions: every time traffic management decisions must be made, all trains that are currently travelling in the infrastructure are considered, plus all the ones that are expected to enter up to the end of the traffic state horizon. All trains are considered from their current position (or from their entrance in the infrastructure if they are not already travelling there) until the end of their journey. The OpenTrack simulator is been used for the three case studies. The EGTrain simulator can be used in its place. Its use in the project has not been possible due to unpredicted delays and scarcity of resources.

At each iteration of the closed-loop, the self-organization process takes place: trains identify their neighbours, generate hypotheses, share hypotheses with their neighbours, check for hypothesis compatibilities, seek a consensus and communicate their chosen hypothesis to the traffic management centre that merges them and if necessary makes adjustments to preserve the feasibility of the resulting traffic plan. All operations are extremely quick and cannot be subject to a time limit, but for hypothesis generation and consensus seeking. For the former, each train executes a variant of RECIFE-MILP in which decisions can only be made within the train neighbourhood. One hypothesis is generated in addition to the one representing the traffic plan currently being implemented, and a time limit of three minutes is set. As for the consensus seeking procedure, trains operate a maximum of 100000 iterations: in an iteration, one train changes its selected hypothesis aiming at achieving compatibility with all its neighbours worsening its cost of delay it suffers, as well as the one of all trains in the system. Indeed, we assume that, even in competition, all trains aim to operate in a system with good overall performance, rather than being the only train on time in a generally very delayed traffic. The classic RECIFE-MILP used as a benchmark is also run for a maximum of three minutes. All procedures stop before reaching the time limit if they find a feasible (consensus) or an optimal (RECIFE-MILP) solution. A further parameter that needs to be set in self-organization is the neighbourhood horizon: two trains are in each other's neighbourhood if they may use at least one common track detection section in the near future, i.e., between the current time and this time plus the neighbourhood horizon. This parameter is set specifically for each case study.

The Pioltello-Rovato case study, whose infrastructure is schematically reproduced in Figure 2, is characterized by the presence of mixed traffic.

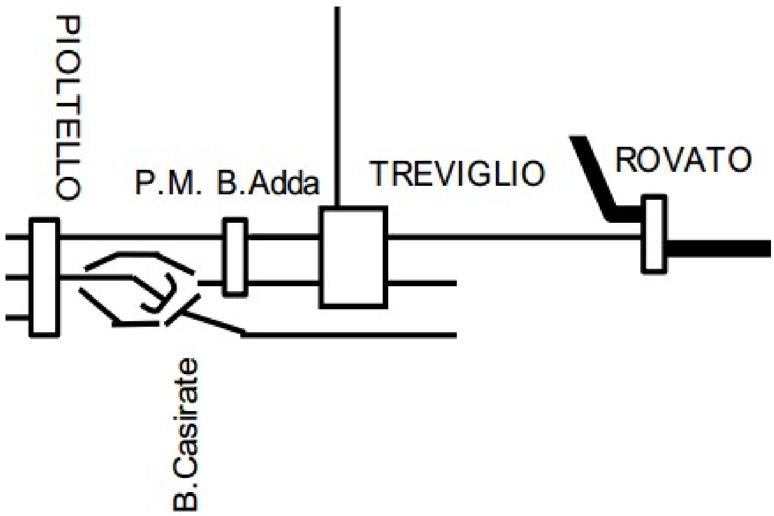


Figure 2. Schematic representation of the Pioltello-Rovato infrastructure

Freight, intercity, regional and high speed trains belonging to different operators share the same tracks. No detailed information is available concerning the historic train loads, be them passenger or freight trains. To reproduce the actual situation in which trains have different costs of delay associated, we assume a linear functional form for this cost and we randomly draw a coefficient for each train. This coefficient depends on the type of train: for freight trains, it is in the interval [15, 24]; for regional trains, it is in the interval [21, 36]; for intercity trains, it is in the interval [19, 27]; for high-speed trains, it is in the interval [24, 40]; for empty rides of passenger trains, it is in the interval [15, 18].

In the perturbation scenarios considered, trains enter the infrastructure with a random delay. The distributions from which entrance delay are drawn are deduced from historical data. They are piecewise uniform distributions, summarized in Table 4. They depend on the type of train and on the entrance point. In the table, we indicate the probability that each train has a delay in the interval heading each column.

Table 4. Probability distributions of train entrance delays in the Pioltello-Rovato case study: probability associated to each origin, train type and delay magnitude

entrance	train	0 sec	Between 1 sec and 5 min	Between 5:01 and 15 min	Between 15:01 and 30 min	Between 30:01 and 60 min	Between 60:01 and 180 min
Rovato	passenger	0.07	0.65	0.21	0.04	0.01	0.02
Rovato	freight	0.31	0.05	0.11	0.15	0.14	0.24
Pioltello	passenger	0.24	0.47	0.24	0.03	0.01	0.01
Pioltello	freight	0.28	0.07	0.10	0.11	0.17	0.27

We consider five perturbations and an horizon of five hours, between 6 and 11am. This horizon covers the peak and off-peak times in the morning. The timetable of these five hours includes 77 trains. To give a visual representation of its density, Figure 3 depicts a space-time diagram of a part of the horizon. As we do not have information of the operator running each train, we assume each train is run by a different operator. To mimic a situation in which operators are in competition, the cost of delay is not shared between trains. Each train knows its own cost of delay and has only a rough idea of the cost of delay of other trains: when optimizing, each train minimized the total assumed cost of delay, in which its own precise function is known (number of seconds of delay multiplied by its cost) and for all other trains an expected value is considered (depending on the type of train, the average cost is considered and multiplied by the number of seconds of delay of the train: 20 for freight trains; 29 for regional trains; 23 for intercity trains; 32 for high-speed trains; 17 for empty rides of passenger trains). In the centralized optimization, no knowledge of different costs of delay is considered, as the information is private.

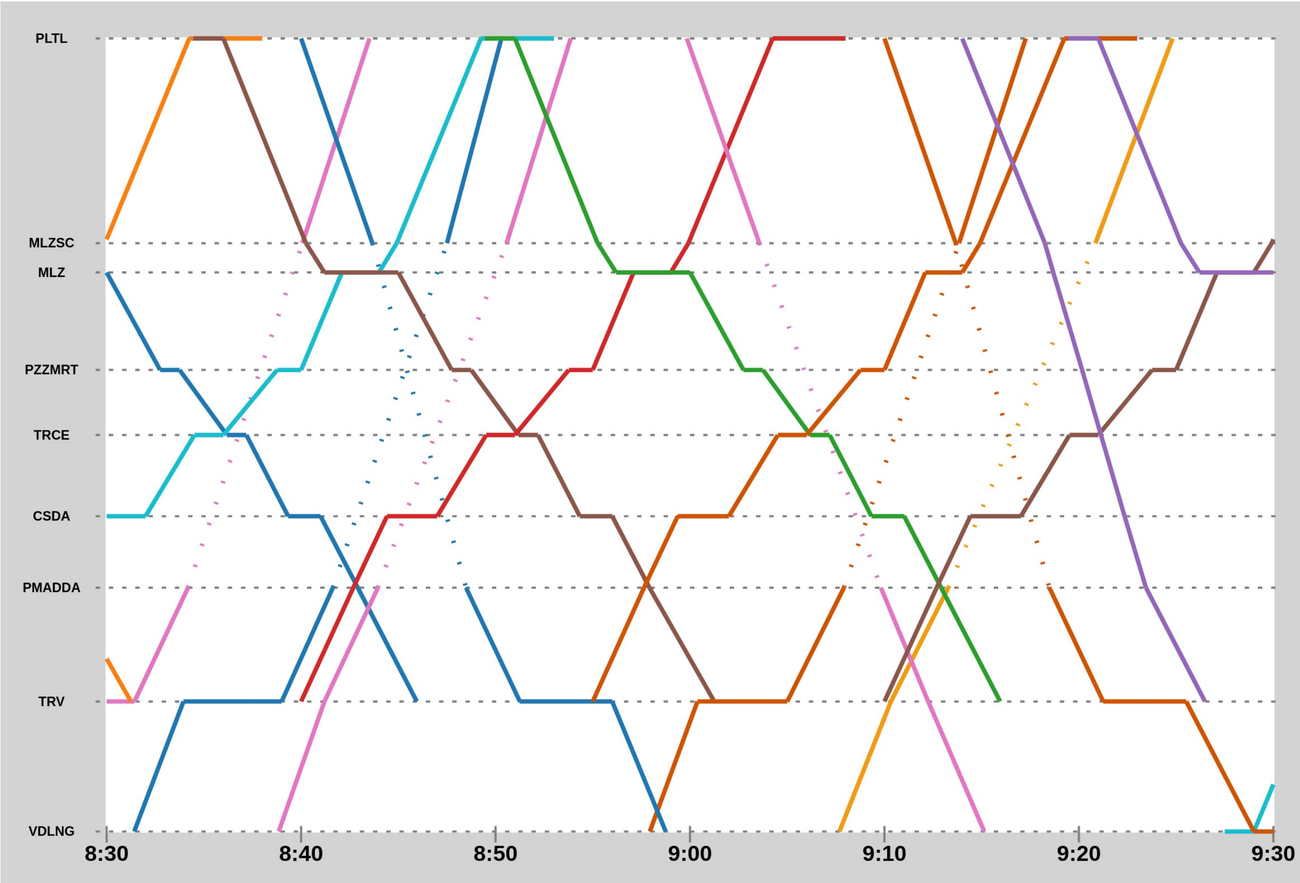


Figure 3. Time space diagram of a portion of the time horizon considered in the Pioltello - Rovato case study

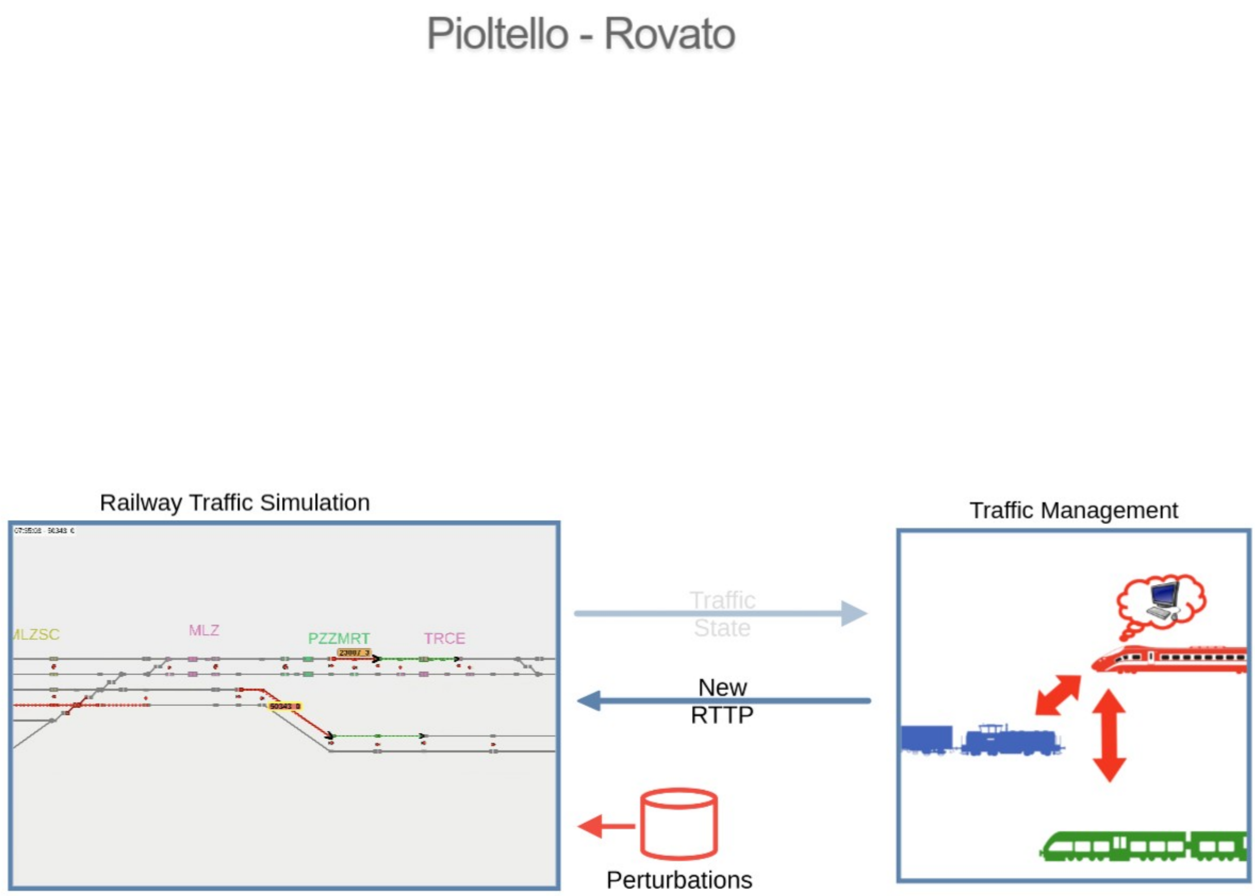


Figure 4. Representation of the closed-loop implemented for the Pioltello - Rovato case study

In the closed-loop, only the traffic simulator and the traffic management modules are active, as shown in Figure 4. The traffic state horizon is set to 45 minutes and the re-optimization period to five minutes. These values are set based on the analysis of the traffic density and of the time trains imply to cross the infrastructure considered. The neighbourhood horizon is set to 10 minutes.

We analyse the results in terms of two KPIs: total train delay and total delay cost. For the latter, we multiply the delay of each train for its cost coefficient, and we sum this value over all trains.

The results for each perturbed five-hour scenario, corresponding to 60 decision making repetitions, are shown in Figure 5. They show that both centralized and self-organized traffic management strongly increase the system performance with respect to the timetable order application. Recall that a total delay of 20% means that the total delay obtained by applying the corresponding traffic management approach is equal to one fifth of the one obtained applying the timetable order. What emerges here is that the centralized optimization and the self-organization achieve results that are extremely similar. Figure 6 and Figure 5 show a closer view of the difference between the two approaches. Here, the difference of delay and total cost of delay is shown: negative values indicate a better performance of self-organization. This figure indicates that, although very small, some difference exits between the results brought by the two approaches. The larger differences are in favour of self-organization when one looks at the cost of delay, with a smaller difference in terms of total delay seconds.

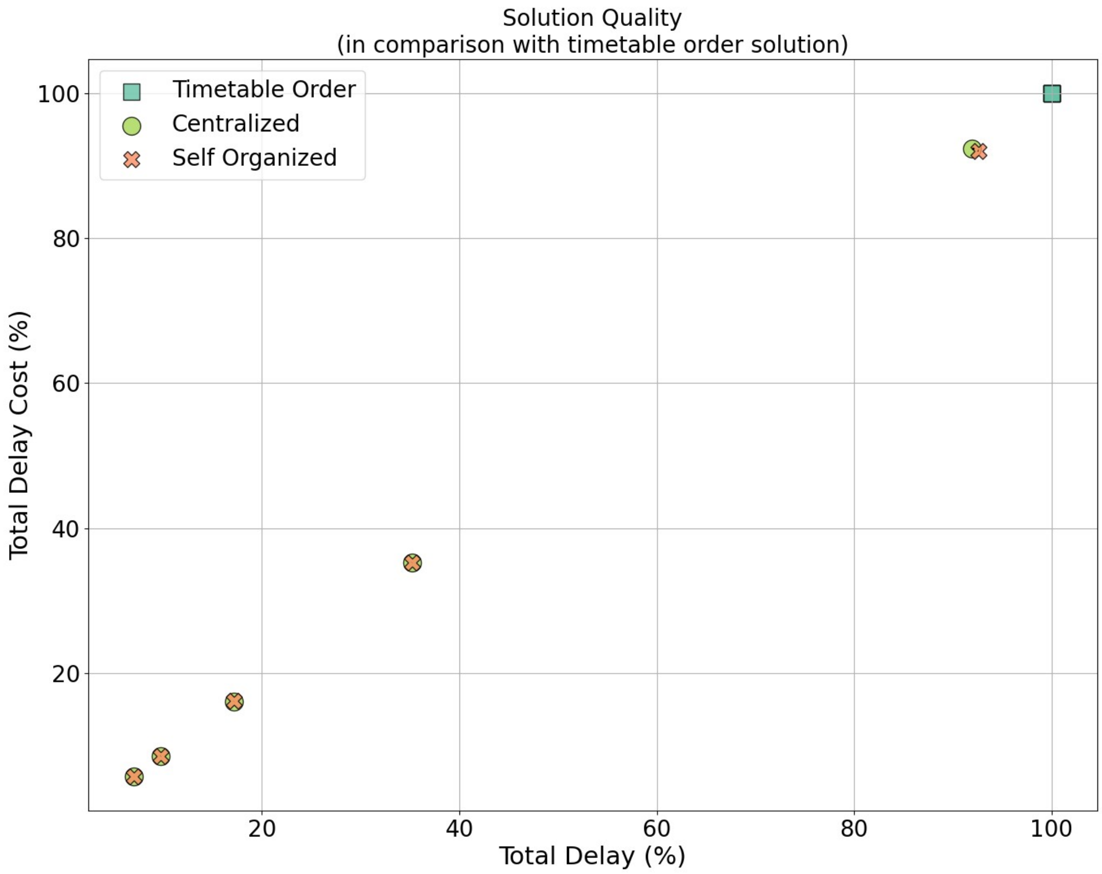


Figure 5. Results for the Pioltello - Rovato case study

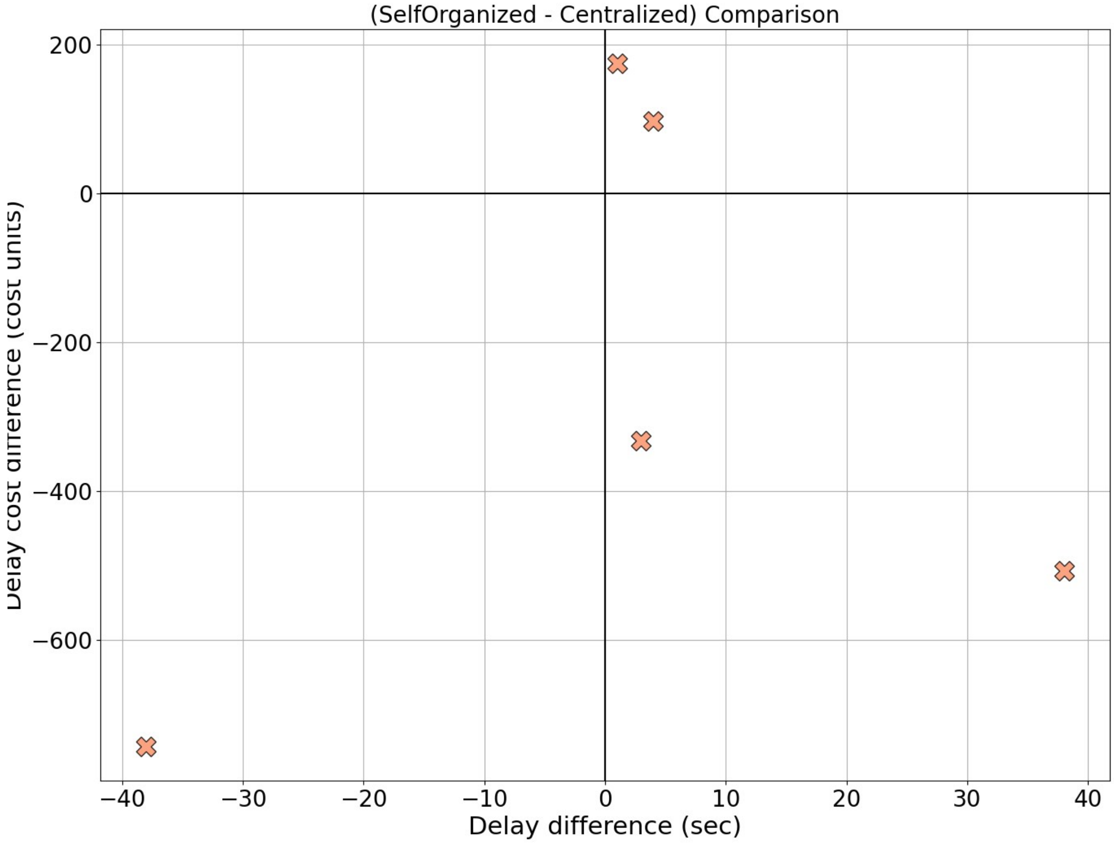


Figure 6. Comparison between centralized and self-organizing traffic management in the Pioltello - Rovato case study

2.2 Guingamp-Paimpol Case Study

The Guingamp - Paimpol case study represents a capillary line with a single track with a limited number of sidings, and few passengers. Despite the little number of passengers, capillary lines play a major role in guaranteeing the territory connectivity. In the Guingamp - Paimpol case study, data on expected passenger flows are generated based on socio-economic reports. This allows the inclusion of passenger simulation in the overall closed-loop framework, as represented in Figure 7.

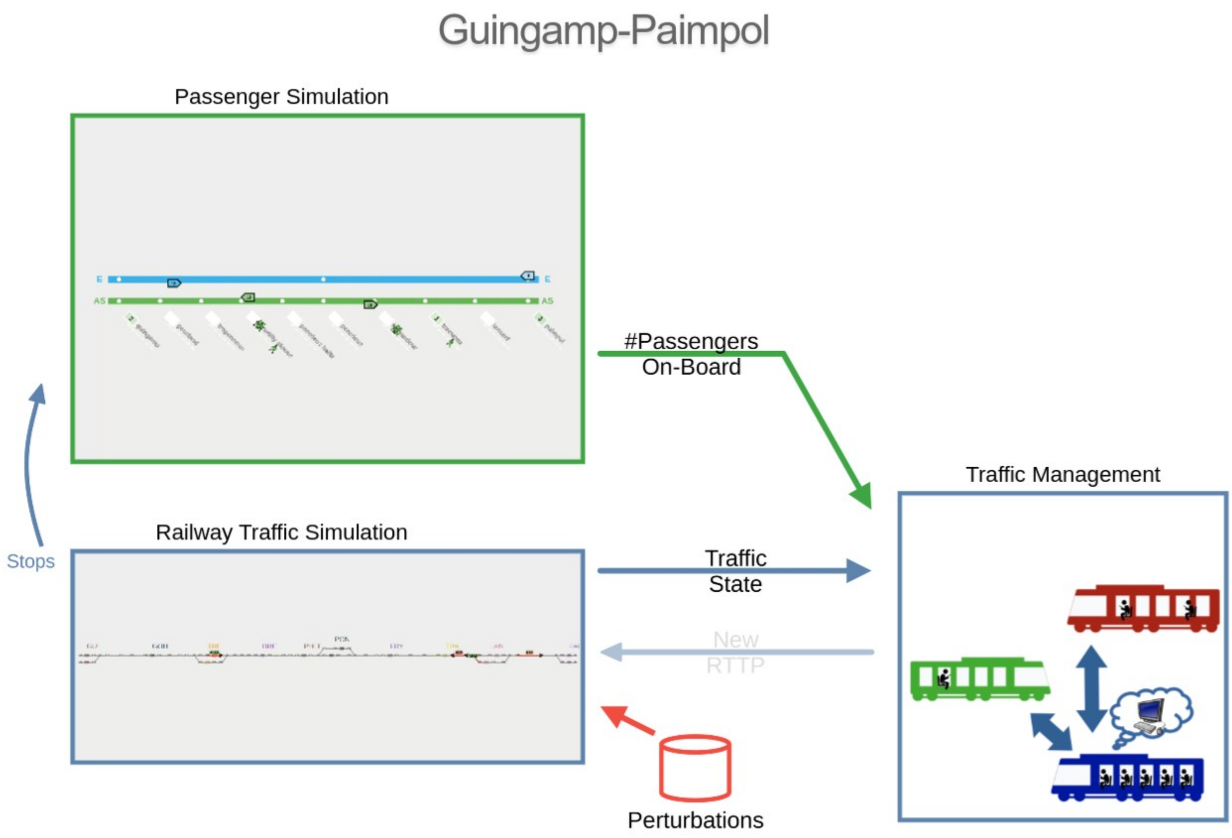


Figure 7. Representation of the closed-loop implemented for the Guincamp - Paimpol case study

Being the infrastructure an single track line, the number of trains that can be simultaneously travelling is quite small. To observe the impact of traffic self-organization on a relevant number of trains, we simulate traffic between 8 am and 1:30 pm, covering the morning peak and off-peak times. In this time, 21 trains circulate and 144 passengers travel in the line. The timetable is depicted in Figure 8 as a time space diagram over a part of the overall simulated time. We consider a traffic state horizon of one hour, a re-optimization period of five minutes, and a neighbourhood horizon of two hours.

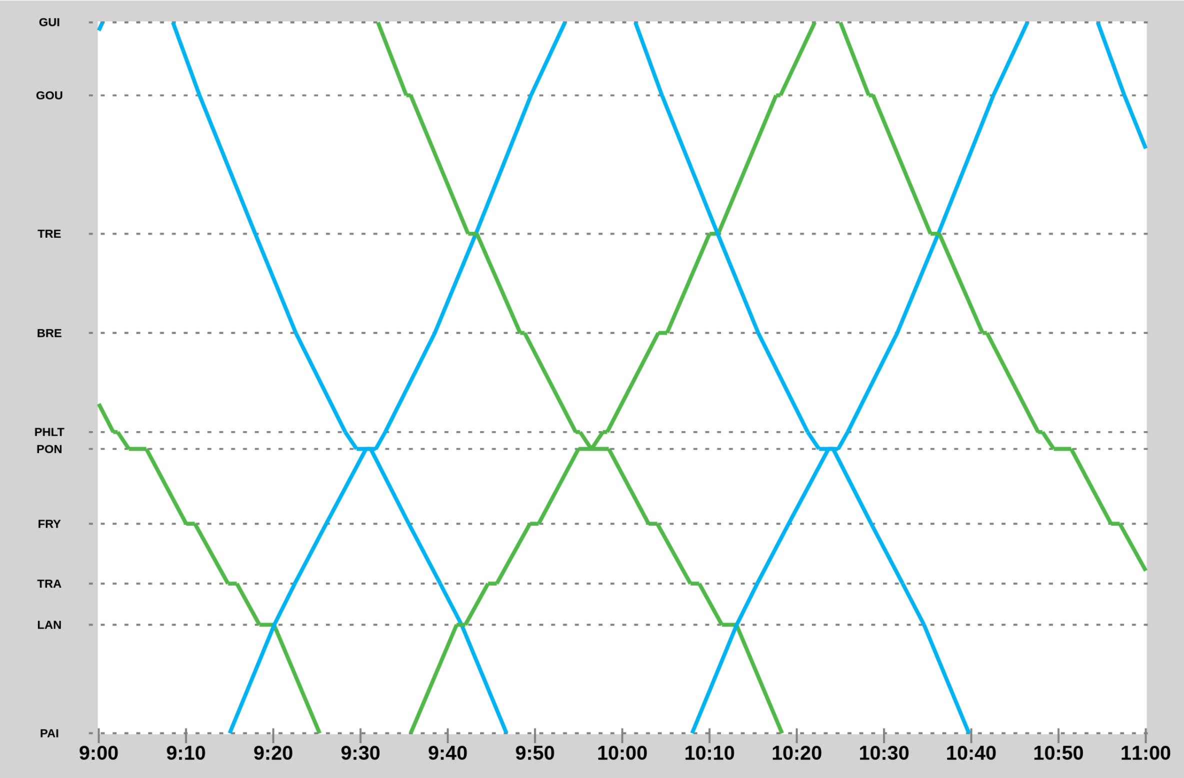


Figure 8. Time space diagram of a portion of the time horizon considered in the Guingamp - Paimpol case study

As no historical data exist on passenger flows, no prediction can be made. To include their consideration in the optimization, as proposed in the SORTEDMOBILITY principles, we imagine a situation in which trains are equipped with passenger counters at their doors. Hence, trains know at any time how many passengers are on-board, but it has no information on the number of passengers that will board later or on where the current passengers will get off. Self-organizing trains have the information on the number of passengers on-board, and consider the weighted sum of trains and passenger delays as the objective function for generating and assessing hypotheses. As a single operator runs all trains, there is no reason to keep this information private, and all trains have full knowledge on passenger presence.

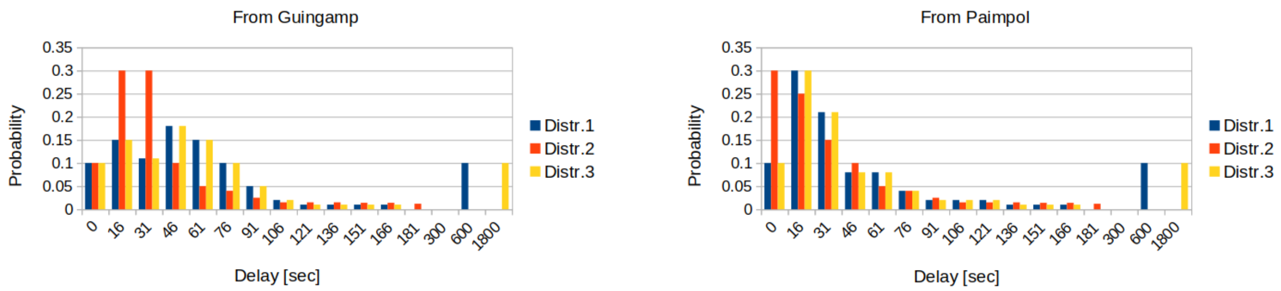


Figure 9. Probability distribution of entrance delays in the first set of scenarios for the Guingamp - Paimpol case study

We generate two sets of perturbations. The first set includes five small entrance delays, following one of the distributions reported in Figure 9 (two scenarios for Distr.1 and Distr.2, one scenario for Distr.3). Here, we indicate the probability that each train has a delay in the interval heading each column. The results obtained in these five scenarios are shown in Figure 10. As in the Pioltello - Rovato case study, the difference between centralized and self-organizing traffic management is very small, both in terms of total delay and of total passenger travel time. In three out of the five scenarios, however, both approaches reach significantly better results than the timetable order. In the two remaining ones, the characteristics of the line imply that the best trains can do, even if some of them is suffering a little delay, is following the original plan in terms of passing orders.

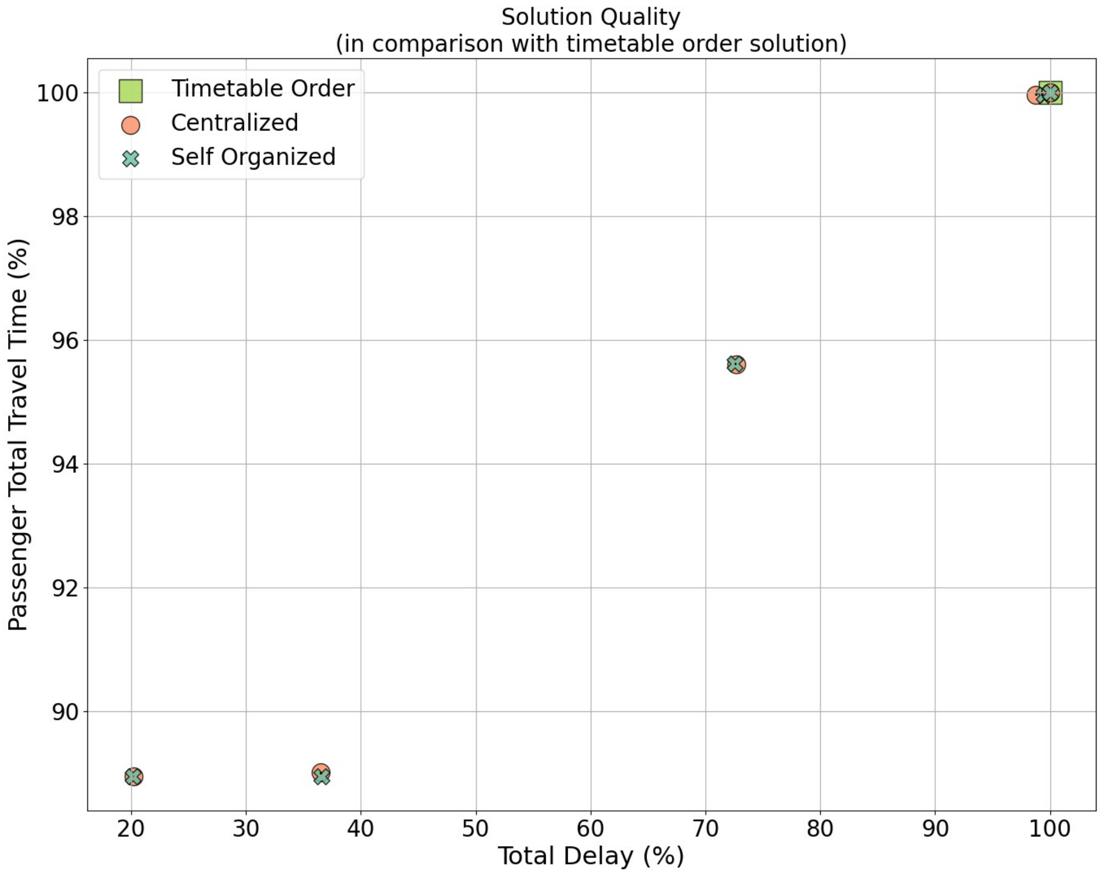


Figure 10. Results for the Guingamp - Paimpol case study. Small entrance delay perturbations.

In the second set of five perturbations, we consider a train stopping in an intermediate station equipped with a siding for a randomly selected duration between 15 minutes and one hour. The results of these further scenarios are shown in Figure 11. Here, the improvements with respect to the timetable order become more remarkable than in the previous results. Moreover, in some cases, self-organization actually manages to improve the passenger travel time with respect to the passenger-agnostic centralized optimization. This comes at the cost of a very little increase of train delays.

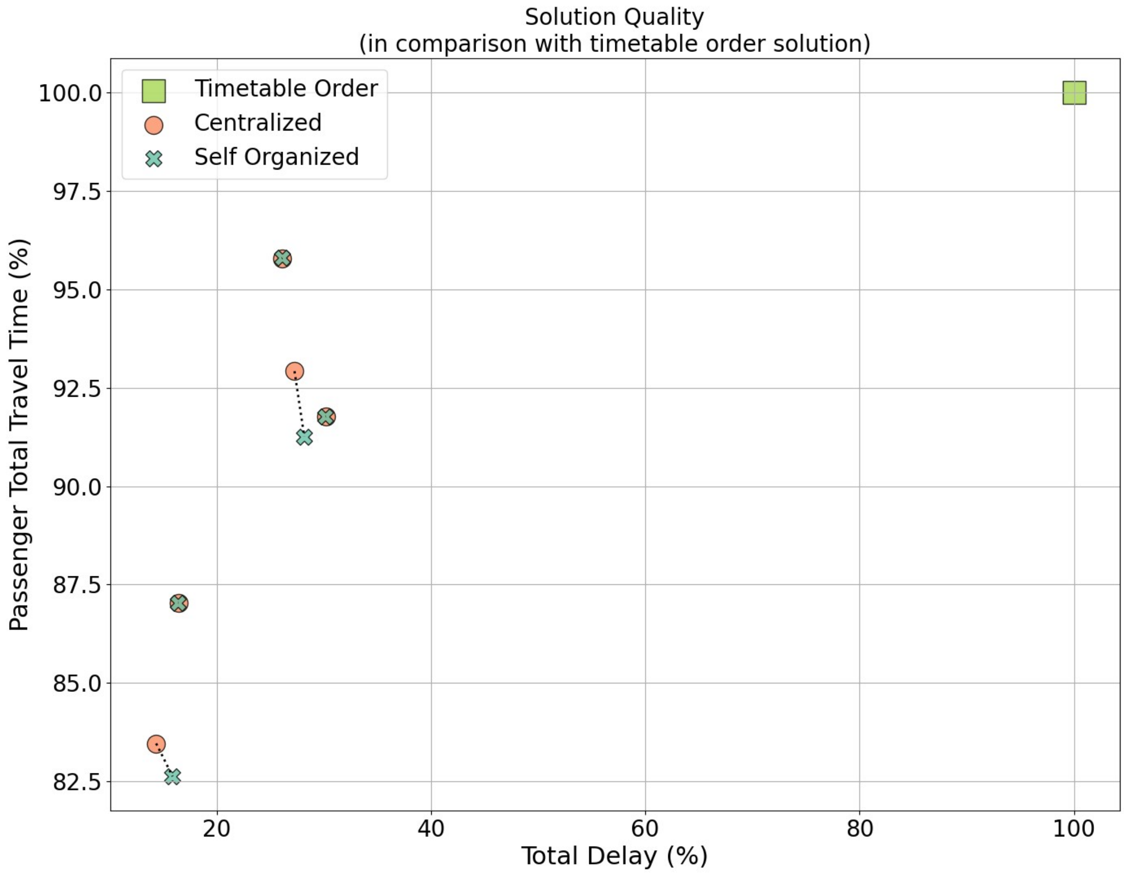


Figure 11. Results for the Guingamp - Paimpol case study. Long train stop perturbations.

2.3 Copenhagen Case Study

The Copenhagen case study includes a very large infrastructure equipped with a CBTC interlocking system. Here, a tap-in-tap-out system is in place for passengers using the nationwide AFC system “Rejsekort”. In SORTEDMOBILITY, we use historical data from these tap-in-tap-outs for predicting passenger flows, as described in D2.2 - Data-Driven Operational Prediction Model (SORTEDMOBILITY Deliverable 2.2, 2023). Moreover, we use a carefully modelled synthetic population for simulating passenger trips in the system (SORTEDMOBILITY Deliverable 2.1, 2023).

In the closed-loop framework, this requires the synchronization of various modules. First, the traffic simulator interacts with a passenger simulator: passengers get on and off trains to reach their destination, using the trains and the connections available and influencing the dwell times at stations. Second, a route choice computation module interacts with the passenger simulator: passengers that have more than one option to reach their destination choose their route based on their own utility function (Sfeir et al., 2024). Also the traffic simulator interacts with the route choice computation module, as passengers base their choices on the observed and predicted train schedule. Third, both passenger and traffic simulator interact with the traffic management module: the simulators supply traffic state and observed passenger flows, the traffic management module supplies train routes and schedules to be implemented. When traffic management is operated through self-organization, it integrates the demand prediction module to the decision making process described in D3.2 - Algorithms for Self-Organizing Railway Operations (SORTEDMOBILITY Deliverable 3.2, 2023).

Figure 12 shows the overall simulation framework implemented for the Copenhagen case study.

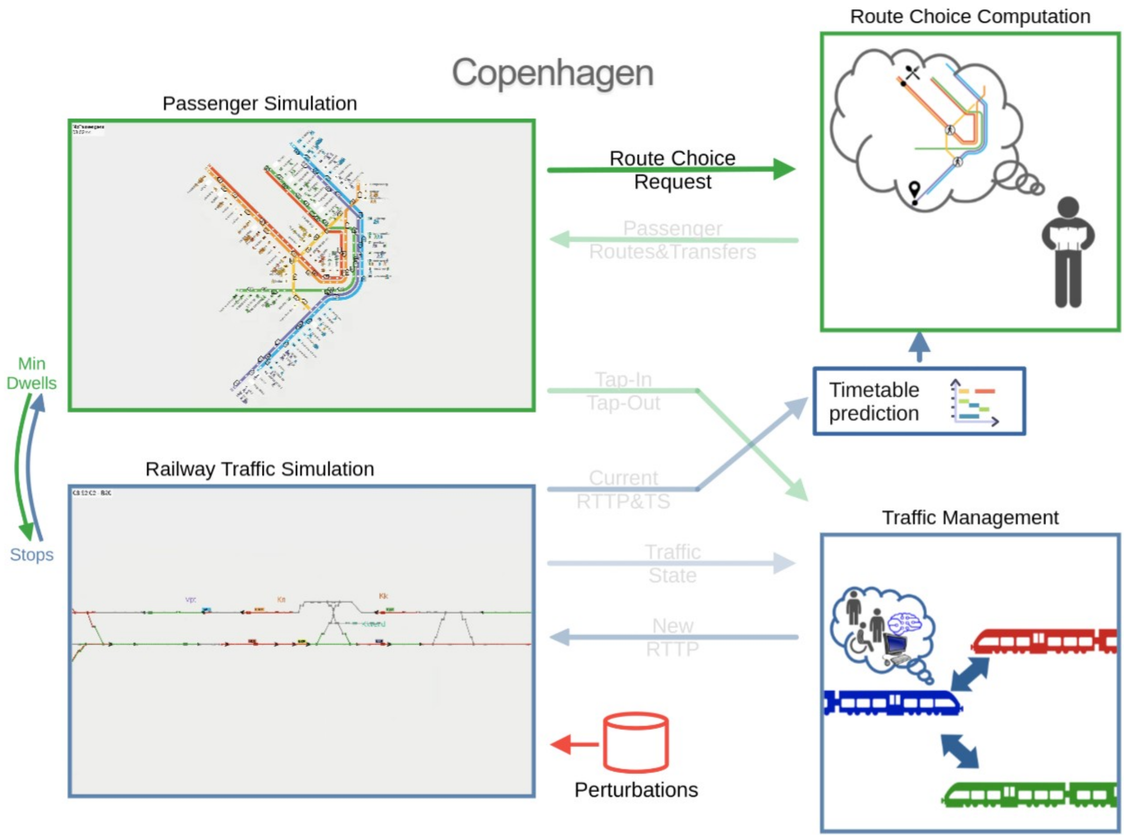


Figure 12. Representation of the closed-loop implemented for the Copenhagen case study

We simulate a time horizon of three hours, between 6:30 and 9:30 am. In this time, 243 trains enter the infrastructure and 15917 passengers travel in the system. A time space diagram representing an hour of planned timetable along the A and E line is shown in Figure 13. It shows the very dense traffic scheduled in the central part of the network, where a double track is shared by all lines. We consider a traffic state horizon of 20 minutes, a re-optimization period of ten minutes, and a neighbourhood horizon of 20 minutes. The demand prediction horizon is, as well, 20 minutes. Figure 14 depicts the macroscopic view of the Copenhagen network.

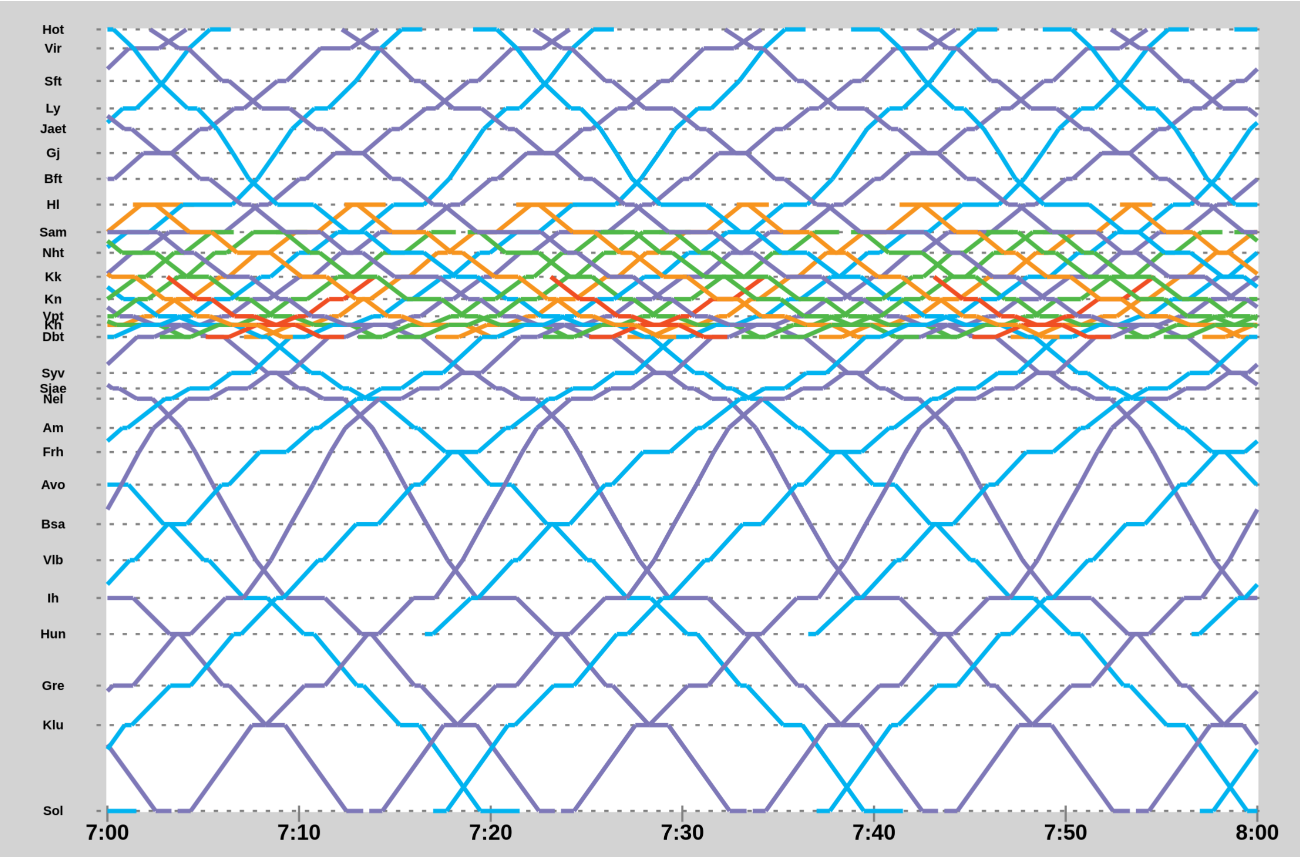


Figure 13. Time space diagram of a portion of the time horizon considered in the Copenhagen case study

Figure 14. Macroscopic representation of the network of the Copenhagen case study

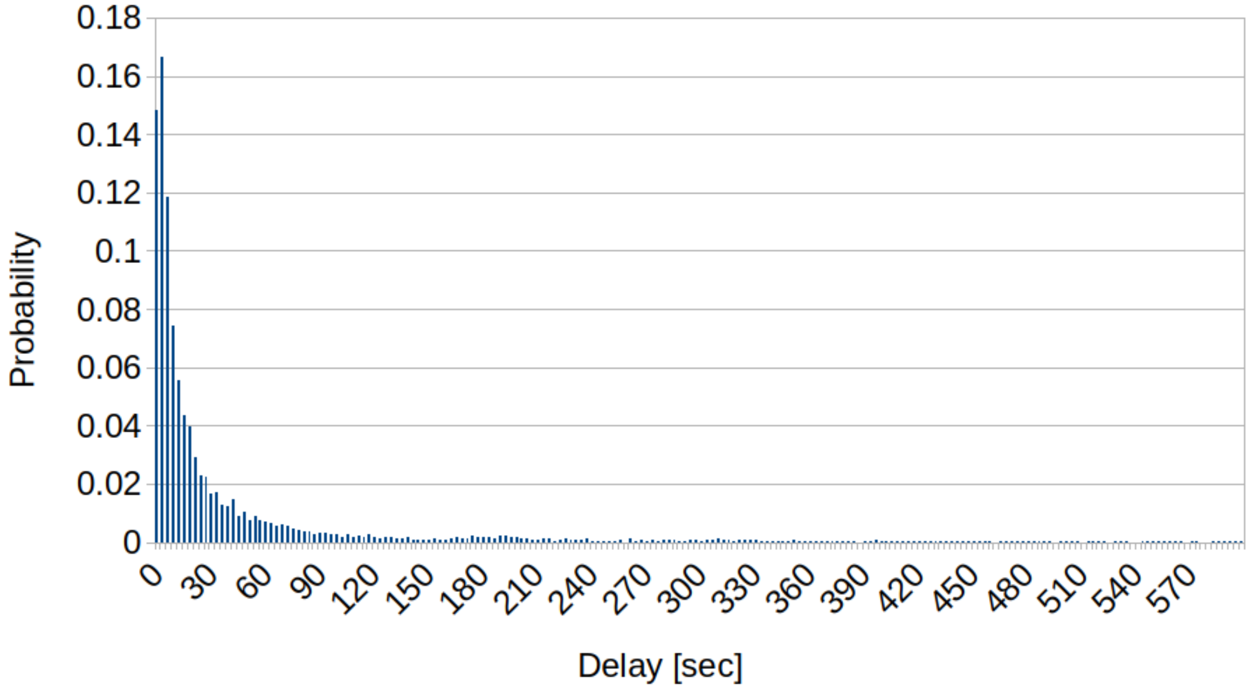


Figure 15. Departure delay probability distribution from Hellerup when a train travels towards Klampenborg

We generate two perturbation scenarios. In each of them, trains may suffer a departure delay from each of their stops. This delay is randomly drawn according to a probability distribution obtained from the study of historical data. A different distribution is used for each station, line and direction. An example is represented in Figure 15. If the number of passengers getting on and off the train implies a long dwell time, the departure times of trains is equal to the maximum value between the planned departure time plus the random delay and the arrival time plus the computed dwell time. In addition to departure delays, we impose a delay of 30 minutes to a train in Lyngby station. The delayed train is one travelling towards the city centre.

We solve the two 3-hour scenarios considering perfect demand prediction: the number of passengers considered by self-organizing trains to generate and evaluate traffic management hypotheses is exactly the number of passenger that will travel in the considered time horizon; the distribution over origin-destination pairs is also exact. Instead, the routing choice made by passengers is unknown: predicted passengers are assigned to each possible route connecting their origin and destination based on the probability they associate to each choice. This probability is proportional to the utility associated to each route, which in turn depends on a combination of factors (travel time, waiting time, number of transfers).

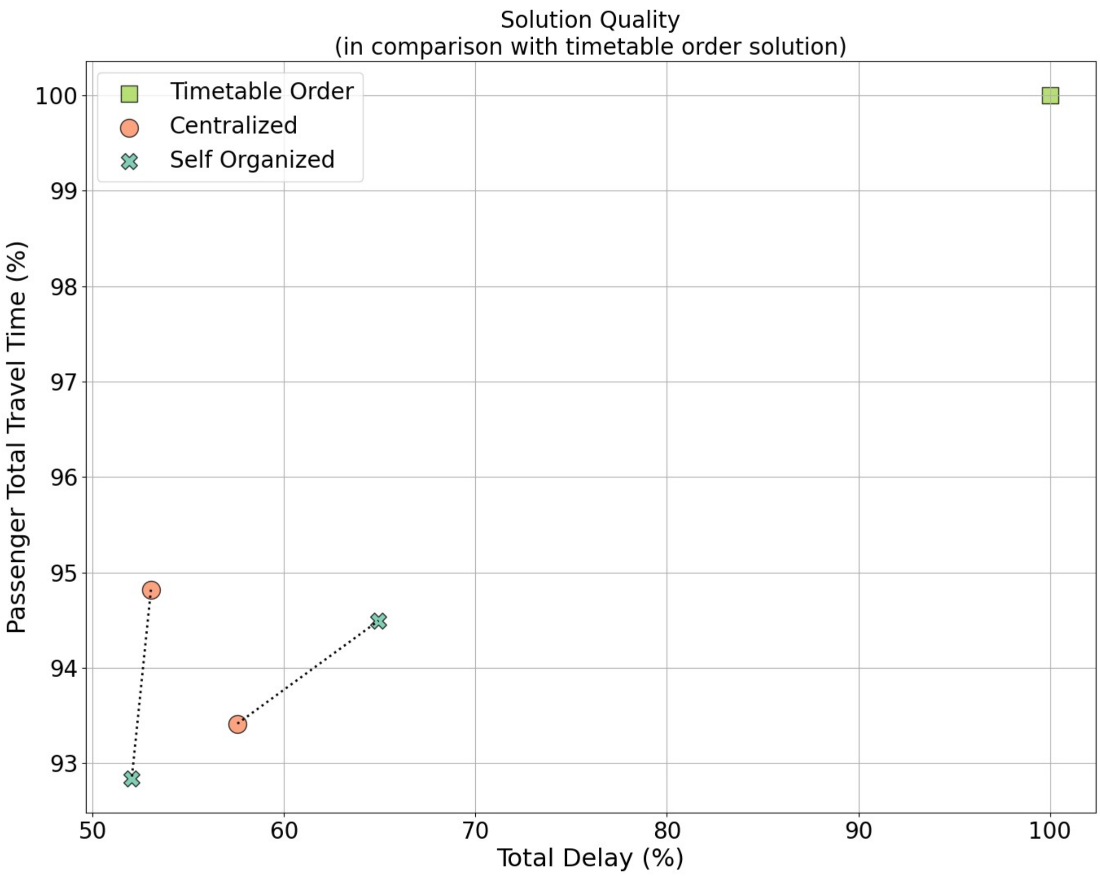


Figure 16: Results for the Copenhagen case study

The results achieved in the two scenarios is represented in Figure 16. In one scenario, let it be scenario A, self-organizing trains achieve better performance than centralized traffic management in terms of both considered KPIs, namely total delay and total passenger travel time. This is possible thanks to two factors. On the one hand, the inclusion of passenger consideration in the decisions making objective function allows trains to rank hypotheses also according to the impact they will have on passengers, and hence to improve the total travel time. On the other had, the natural decision making decentralization coming with self-organization allows a better scaling: at the peak time, when more than a hundred trains circulate in the infrastructure, the centralized optimization fails in finding the best rerouting solution for a couple of trains, while the trains themselves manage to spot it. In the second scenario, let it be scenario B, instead, self-organization achieves worse performance than centralized optimization. After studying the details of the traffic management decisions made, we realized self-organization suffers from a border effect on passenger prediction. In particular, the main difference in the traffic management decisions made by the two approaches concerns two trains, EB11 and B17, when they reach the junction leading to the common part of the network in the city centre (at 7:50 am). When they reach this point, centralized optimization lets B17 pass first. Instead, trains reach a consensus on Eb11 passing first: it has many more passengers on board than B17, and this situation is expected to persist for the coming 20 minutes, which is the duration of the demand prediction used to assess hypotheses. However, after these 20 minutes, from around 7:26 am, an opposite situation emerges: many passengers are travelling on line B, and only a few on line E. Hence, a large number of passengers suffer from the fact that B17 is delayed, while only a few profit of the priority given to Eb11. The number of passengers on the two trains are represented in Figure 17 and Figure 18. We call this issue a border effect because an easy way to solve it would consist in extending the time horizon for demand prediction to, e.g., half an hour. By doing so, trains would know that B17 shall not be late because it will be needed by many passengers, and they would let it pass first. However, no guarantee exists on the fact that considering an horizon of half an hour would not create an equivalent issue at some other time or location: the only guarantee would be possible if complete omniscience was available at any time, but this of course is not a realistic assumption. In future research, we will work to identify ways for mitigating the impact of border effects.

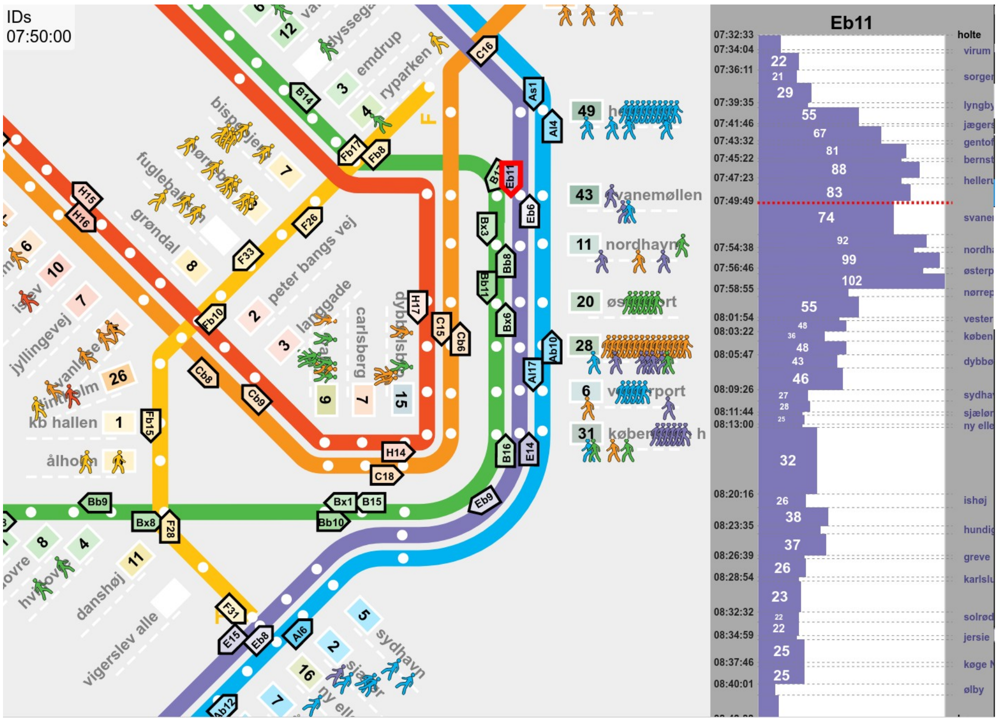


Figure 17. Passengers in train Eb11 in scenario B of the Copenhagen case study

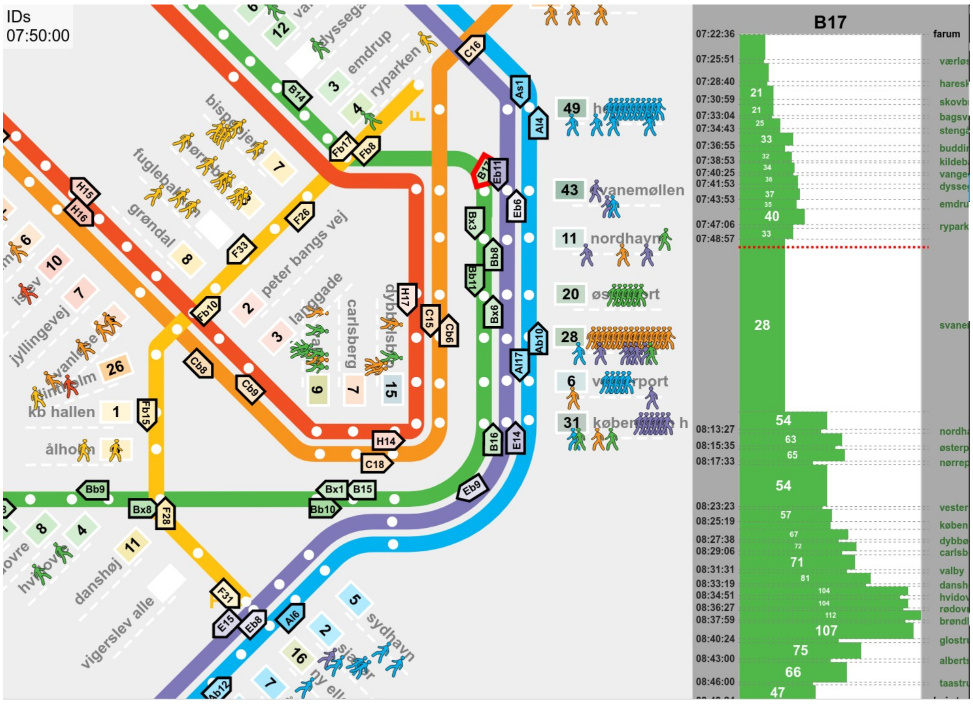


Figure 18. Passengers in train B17 in scenario B of the Copenhagen case study

As a second experimental analysis focusing on the Copenhagen case study, we replicated the above described set-up in a small part of the network chosen to preserve interesting passenger behaviours while limiting the scale of the system. The considered network is represented in Figure 19. In the following, we refer to it as *tiny Copenhagen.* The difference between the set of experiments on tiny Copenhagen and the previously presented ones consists in the demand prediction module. While we previously considered a perfect prediction, we use here a Graph Convolutional Network-based prediction in tiny Copenhagen, as presented in D2.2 - Data-Driven Operational Prediction Model (SORTEDMOBILITY Deliverable 2.2, 2023). Moreover, passengers can choose whether to change their route whenever their train suffers a minute or more of delay increase between two consecutive stops.

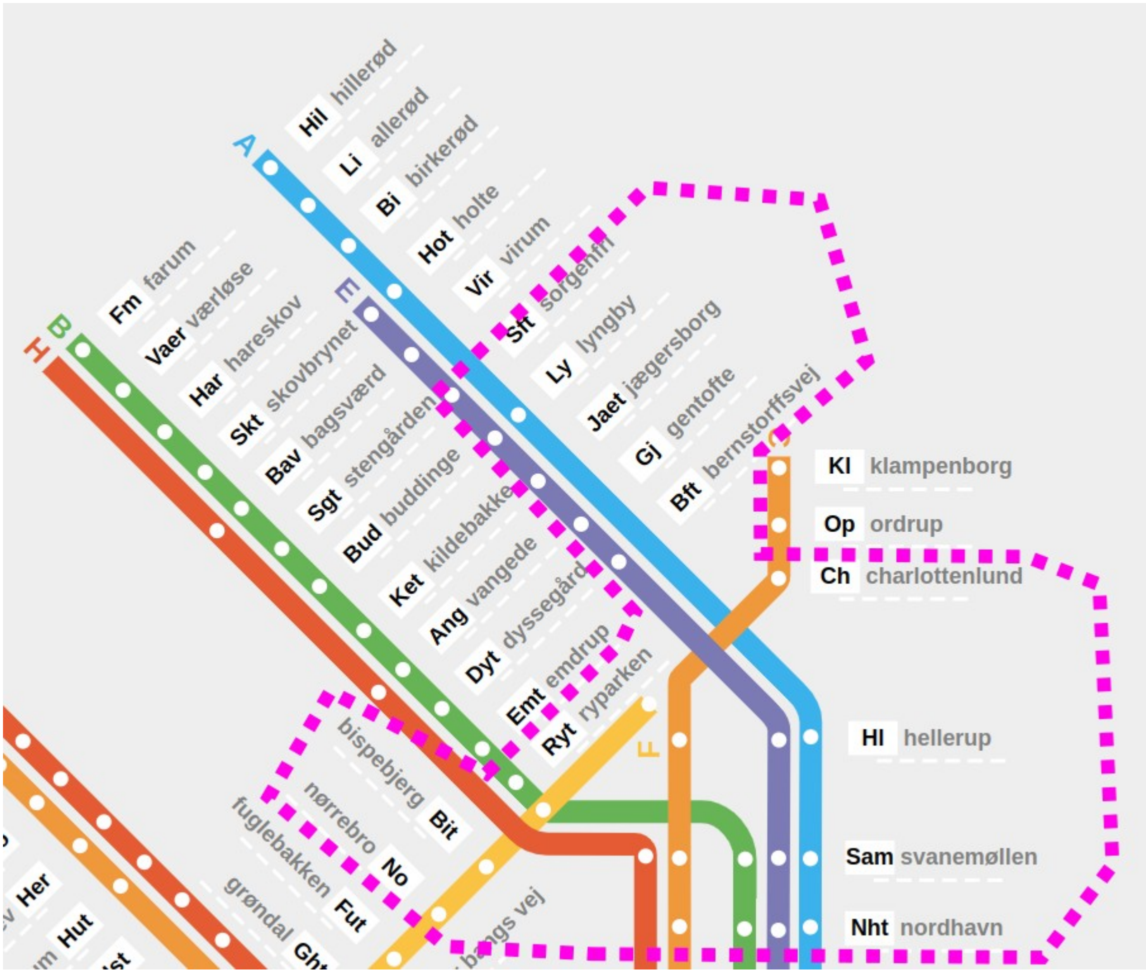


Figure 19. Part of the network corresponding to the tiny Copenhagen study

The results achieved by self-organization in the two scenarios in tiny Copenhagen are shown in Figure 20. Although the differences are smaller than in the Copenhagen case, the same observations can be made here: the performance of both centralized optimization and self-organization are remarkable better than the timetable order, and none of the two approaches outperforms the other on both scenarios. The unavoidable imprecision of the demand prediction and the additional variability due to passenger re-routing do not have a remarkable negative impact on the results.

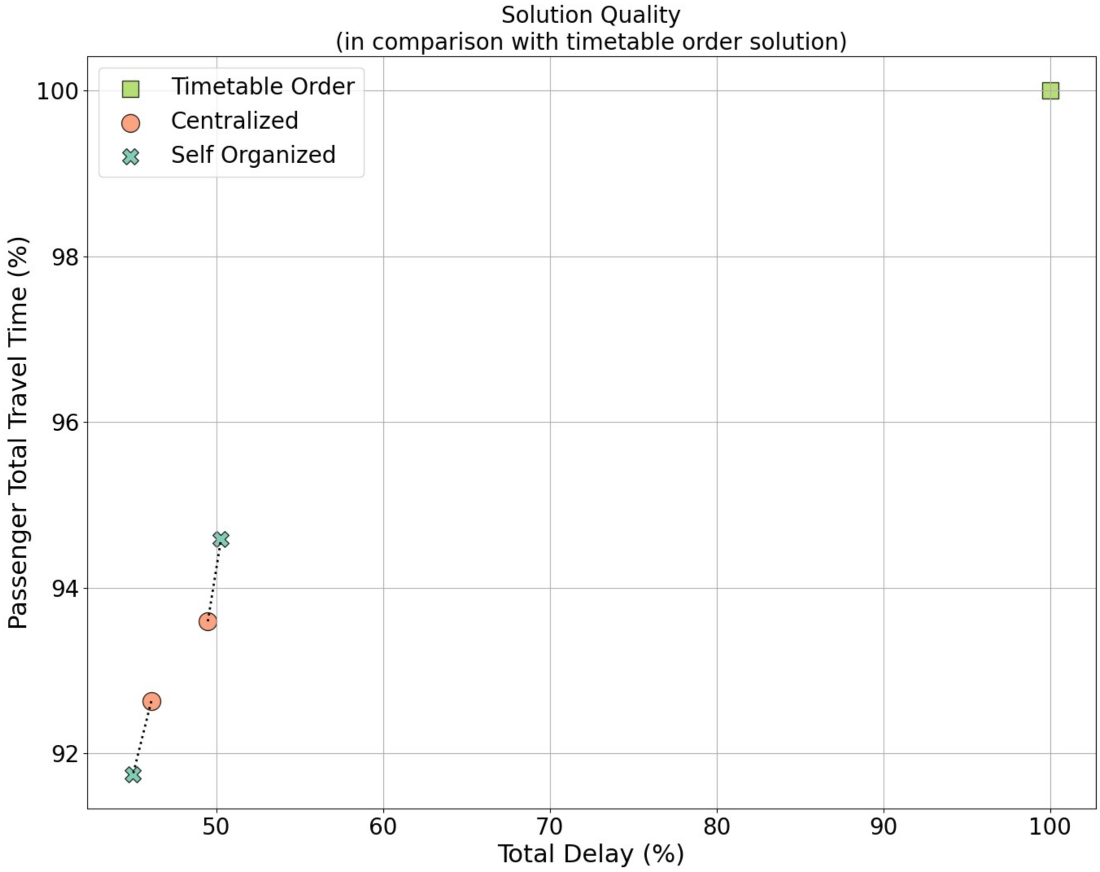


Figure 20. Results for tiny Copenhagen

In the future, it will probably be possible to improve the results of self-organization by working on the specific algorithms implementing the process. However, as far as the centralized system is not overwhelmed by the excessively large size of the instances, it is unlikely that self-organization will manage to obtain better results than a centralized system. Indeed, the centralized system and its processes are already designed to maximize performance on clearly identified KPIs.

Nonetheless, self-organization may allow the achievement of very interesting results on KPIs which are not monitored so far, remarkably largely better than centralized optimization: we think, in particular, to KPIs related to the robustness or to the resilience of the system. We are convinced that self-organization could avoid or at least mitigate knock-on effects and the rapid propagation of negative effects of disturbances and disruptions into the network.

Still about KPIs, we think a major difference can be made also with respect to equity. In a context of competition, a question that arises nowadays is how the infrastructure manager can guarantee the fair treatment of different railway companies, while optimizing the performance of the system. This is a very sensitive issue. Indeed, railway companies want a guarantee of being treated fairly by the infrastructure manager. We think that the concept of consensus driven by self-organization could precisely answer this question given that the railway companies would contribute to the decision-making process with their own objectives. As shown in the Pioltello - Rovato case study, self-organization can facilitate fairness without worsening the performance of the overall system.

The Guingamp - Paimpol case study showed that self-organization can successfully manage traffic on small lines. In many countries, small lines represent a non-negligible portion of national networks. In France, for example, they correspond to around one third of the network. We see a clear opportunity to exploit them with a self-organizing system for different reasons:

- form the railway operator point of view, we can assume that a self-organizing system would be quick to deploy, allowing operators to have different operational objectives on different lines, whether for passengers or for freight, and whatever the transportation plan.
- from the IM point of view and related to the human factor, it is difficult for traffic controllers to stay focused on areas where there is little traffic. So, the implementation of a self-organized system that could relieve them of these tasks could be definitely beneficial.

In this way, it would be possible to operate small lines without additional resources from the IM. Regulators and traffic controllers could remain focused on areas where there is the most traffic. Moreover, the operations costs could be limited to those carried by the railway operators. That would be a significant advantage for the IMs and it could be an opportunity to revive the small lines.

Finally, dense networks where passenger information is available, may benefit from the self-organization process proposed in SORTEDMOBILITY from two perspectives. On the one hand, self-organization eliminates the issues related to the increase of the size of the instances, which undoubtedly makes centralized optimization problematic today. On the other hand, the consideration of demand during decision making does not add a significant computational burden while potentially allowing a great improvement of the results from the passenger perspective.

3 GUIDELINES AND RECOMMENDATIONS FOR A SELF-ORGANSING RAIL TRAFFIC MANAGEMENT

The objective of the research task described in this section is to provide a set of guidelines and recommendations for further development of self-organising rail traffic operations. To achieve that objective a preliminary analysis has been made to identify potential advantages and limitations which railway experts and stakeholders currently see in a self-organising rail traffic paradigm with respect to the state of practice. The analysis includes experts' view on the main gaps in current rail traffic management (TM) and potential roles that rail self-organisation might have in achieving the EC's White paper (2011) goals set for 2035 / 2050 on transport sustainability and competitiveness. Specifically, a multi-target Delphi analysis is used to achieve three main targets, namely the evaluation of: 1) current TM gaps and potentials of rail traffic self-organisation, 2) strengths, weaknesses, opportunity and threats (SWOT) of such a traffic paradigm and 3) recommendations for migrating to a self-organising traffic management.

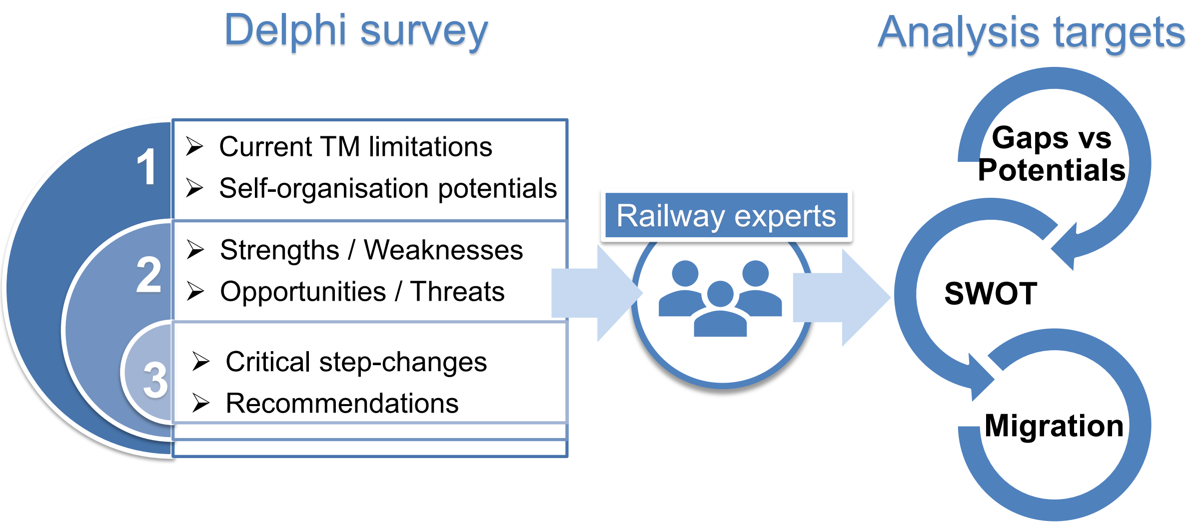


Figure 21. Multi-target Delphi analysis used to analyse current TM gaps, potentials and migration to self-organising rail traffic paradigm.

A Delphi survey has been hence submitted to a group of international railway and transport experts. The distributed survey is arranged in three parts, corresponding to each of the three analysis targets, as described as follows:

i) The first part aims at identifying limitations / gaps in existing rail traffic management and possible benefits that rail traffic self-organising could bring towards the vision of a sustainable, competitive multimodal transport network.

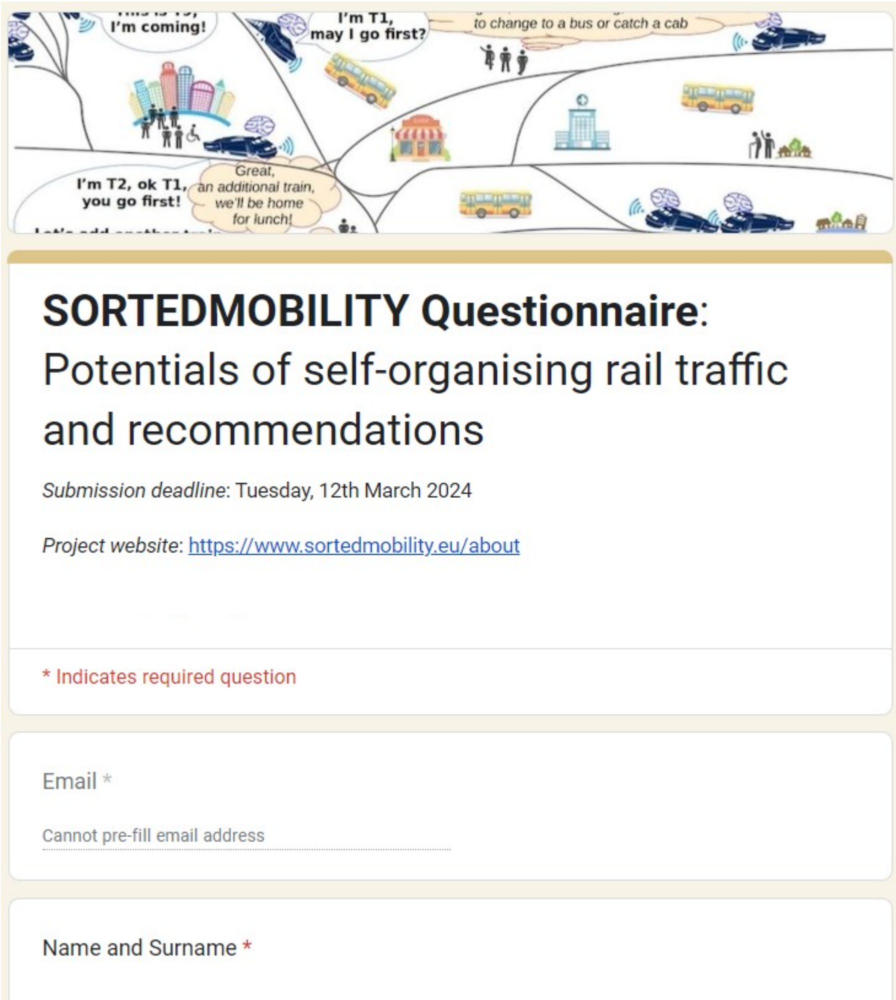
ii) The second part includes a SWOT analysis which delineates main advantages, limitations as well as business/ organisation opportunities and risks that railway experts consider for self-organising rail traffic management.

iii) The third part instead focusses on defining main step changes and critical requirements necessary to a potential migration from the current state of practice to a self-organising rail traffic management paradigm.

The next subsection describes in detail the setup and the structure of the Delphi interview while the successive subsection (4.2, 4.3 and 4.4) reports in detail on each of the three above mentioned parts of the analysis.

The three parts of the analysis described in the previous section are based on a Delphi interview which has been made to a group of 7 international transport stakeholders and railway experts from both academia and industry. Interviewed experts are either members of the consortium or part of the advisory board of SORTEDMOBILITY project. Specifically the group of interviewees included representatives of the European railway industry including Infrastructure Managers (IMs), Railway Undertakings (RUs) as well as rail experts from academia (both professors and researchers).

Before conducting the interviews a specific workshop has been held online (on the 1st of March 2024) to provide interviewees with sufficient background knowledge about project content as well as with an explanation of the interview's objectives. The main aim of the workshop was to reduce potential bias in interviewee's answers due to question misinterpretations or insufficient background information about the topic and/or the progress of the project.



SORTEDMOBILITY Questionnaire:
Potentials of self-organising rail traffic and recommendations

Submission deadline: Tuesday, 12th March 2024

Project website: https://www.sortedmobility.eu/about

* Indicates required question

Email *

Cannot pre-fill email address

Name and Surname *

Figure 22. Screenshot of the online SORTEDMOBILITY questionnaire on potentials an recommendations for self-organising rail traffic

Interviews have been collected by means of an online questionnaire (SORTEDMOBILITY questionnaire, 2024), of which a screenshot is illustrated in Figure 22. The questionnaire is composed of a total of 6 questions, namely:

Q1. What are in your opinion the main challenges / limitations regarding current rail traffic management and how those affect the achievement of the EC goals for a competitive, efficient multimodal transport?

Q2. Would self-organising rail traffic management help overcoming current limitations? If so, can you explain how and the potential benefits in achieving the EC’s White paper goals?

Q3. Which are according to you three main strengths and three main weaknesses of self-organising rail traffic management with respect to current practice?

Q4. What are instead three main opportunities and three threats that self-organising rail traffic management can lead to?

Q5. Can you mention three main necessary step changes and/or transitions before current railways can be migrated to a self-organising traffic paradigm?

Q6. Can you think of two essential recommendations and/or system requirements that will facilitate the introduction of/migration to self-organising traffic management in railways?

As can be seen, the submitted questionnaire has the main objective of collecting expert opinions on whether and how a self-organising rail traffic paradigm could improve current railway operations and facilitate the achievement of the EC's strategic goals on transport sustainability and competitiveness.

In addition, the questionnaire is also addressed to gather necessary recommendations for further investigation of the self-organising concept as well as requirements to a potential migration to a more flexible, interconnected and sustainable rail transport system.

2.2 Gap analysis of current state-of-practice and potentials of self-organizing traffic management towards EC White paper's goals.

Experts' responses to questions Q1 and Q2 of the SORTEDMOBILITY questionnaire have been elaborated to identify gaps in current rail traffic management and advantages of traffic self-organisation in relation to the EC White paper goals. The distribution of answers collected in relation to main gaps / limitation of existing rail traffic management practices is illustrated in Figure 23.

The majority of the interviewed railway experts (71.4%) considers that the main limitation of current rail traffic management in achieving the EC white paper goals stays in legal and/or technological barriers in sharing transport data within the railways and with other transport modes. A major limitation (identified by 57% of the interviewees) is also seen in the current legal / technical split in responsibilities between IMs and RUs imposed by the existing competitive rail market structure. Most of the respondents seems to find that the current railway organisation (where IMs are separated by RUs and multiple RUs compete against each other) limit the open data sharing necessary for an integrated and sustainable multimodal transport system. Another identified gap (43% of the respondents) is the missing link between planning / management of railway traffic and other transport modes, which limits synchronisation / coordination of multimodal passenger and freight connections. Additional limitations are also found (by 43% of the interviewed sample) in the poor digitalisation level of existing railways together with current distrust of rail planners / dispatchers in tools for automated traffic management. A correlation possibly exists between these two latter gaps. The reluctance of railway planners/dispatchers in accepting automated rescheduling tools might indeed be one of the causes for the slow digitalisation process in railways.

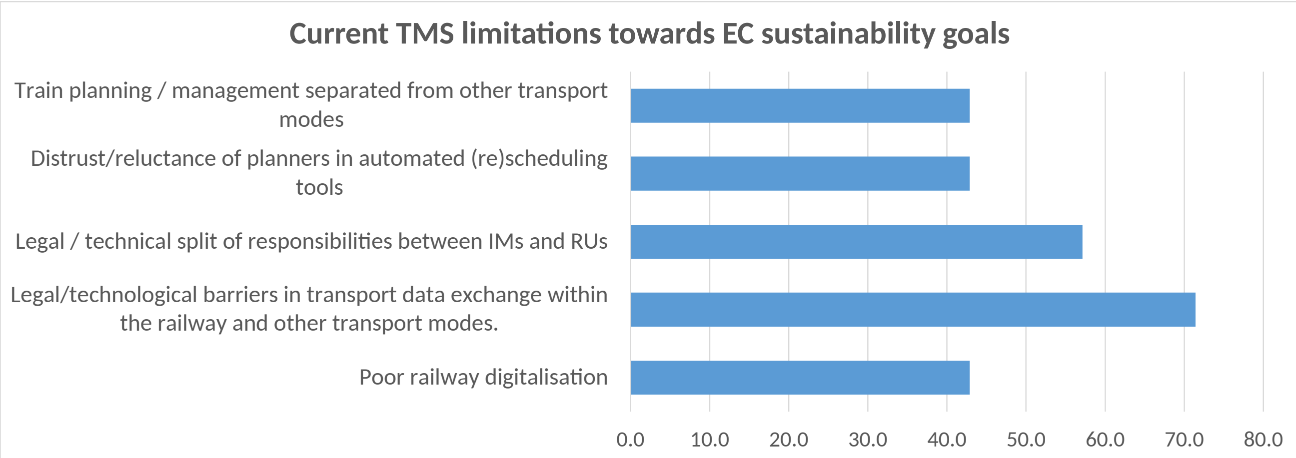


Figure 23. Distribution of expert responses on current TM limitations

In answering question Q2, the totality of the interviewees believes that the deployment of a self-organising rail traffic paradigm per se, would not necessarily overcome current TM limitations towards achieving EC's White paper goals. Interviewed experts do recognise that self-organisation can lead to a more balanced workload distribution among dispatchers and to an improved railway traffic responsiveness / resilience to disturbances, thanks to reduced complexity of the train scheduling problem (which shifts from the whole network to a more local area). However, only changing the paradigm of how rescheduling decisions are taken, is not believed to be enough to achieve a multimodal and sustainable transport system as targeted by the EC in 2035 / 2050. According to all the respondents, self-organisation could significantly contribute to overcome current limitations and achieve EC's strategic goals, if it facilitates addressing current critical needs in the railway industry. As illustrated in Figure 23, the majority of the experts (71%) self-organisation could overcome existing limitations in achieving EC's strategic targets if it fast-forwards the implementation of digital platforms and regulations enabling open, transparent information sharing on passengers, resources and train rescheduling criteria. Such a response matches what the experts have reported as the main gap in current rail traffic management, being legal / technological barriers in open data sharing among the different stakeholders.

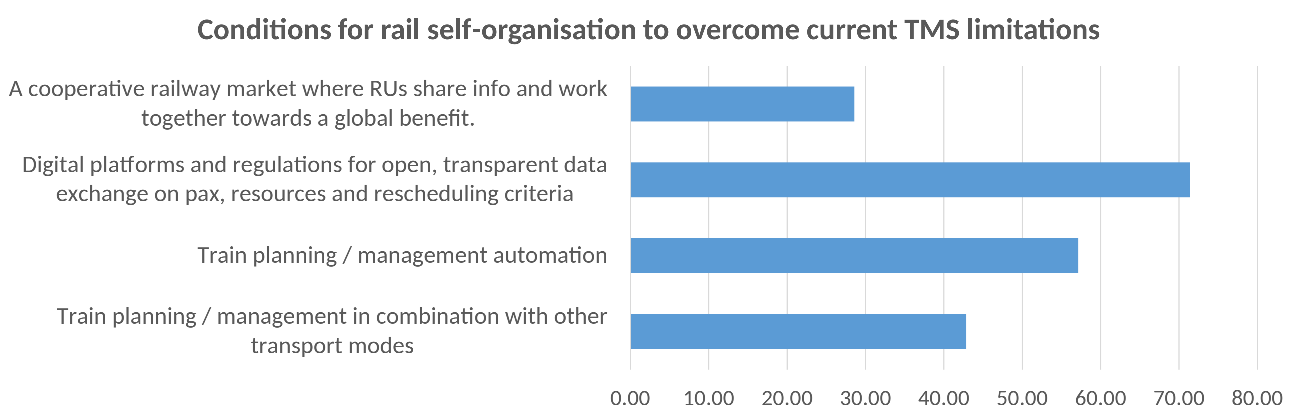


Figure 24. Conditions which self-organising rail traffic should facilitate to overcome current TMS limitations in relation to EC's White paper goals.

A train planning / management which is both automated (57% of the interviewees) and synchronised with other modes of transport (43%) is also considered to be essential to allow a self-organising paradigm to make a difference towards the achievement of the EC White Paper targets. Such answers are again well aligned with the gaps identified by the experts in relation to the current need of combining train planning / management with other transport modes and increasing digitalisation levels of the railways.

The migration to a cooperative rather than competitive rail market is also found (by 29% of the respondents) as a need that rail traffic self-organisation should help addressing. Such a market structure could facilitate RUs in defining negotiation processes and policies which can be beneficial for all involved decision-makers rather than the individual.

2.3 SWOT analysis of self-organising rail traffic management

A SWOT analysis has been performed based on the answers provided by the interviewed experts to questions Q3 and Q4, respectively regarding the identification of strengths / weaknesses and opportunities / threats of self-organising rail traffic management. Collected responses have been processed and summarised in Table 5.

Table 5. Strengths, Weaknesses, Opportunities and Threats identified for self-organising rail traffic management

Strengths	Weaknesses
• Flexibility to demand variations and to local supply disturbances / faults • Scalability to different areas and traffic density and infra complexity. • Increased efficiency in defining traffic management strategies to tackle disturbances/ disruptions • Actor negotiation keeps transparent decision-making of train priorities. • Consideration of individual needs in the negotiation of train rescheduling strategies • Transparent info sharing among multimodal transport services and operators	• Need of communication interfaces for effective and efficient train negotiation • Limitation in identifying globally-optimal train rescheduling strategies. • Prone to bias from self-declared importance if not all actors play by the rules. • Difficult control of effect of local train negotiation over whole network capacity and performances. • A shared consensus among trains might not be found for the current competitive rail market model.
Opportunities	**Threats**
• Opening R&D directions for efficient and flexible rail traffic management approaches. • Extendibility of self-organising approaches to other sectors • Opening to passenger-oriented / customer-centric service rail market • Fast-tracking resilience improvement of low complexity / low traffic density markets where the concept could be easily tested. • Facilitating deployment of automated depots thanks to train communication protocols improving rolling stock coordination. • Increased market accessibility to new /smaller competitors / operators. • Larger attractivity and competitiveness of the railways. • Improved coordination between train service planning and operations thanks to increased RU's responsibilities.	• Potential failure of early pilot tests might limit future R&D in this field. • Negotiated rescheduling strategies might be unclear and protested. • Regulatory approvals and standardisation of comm. / data protocols might be difficult and long • Risk of ambiguous responsibility identification in case of disruptions / accidents. • Additional communication protocols might add cybersecurity risks of biased / dangerous train negotiation processes • IM's reluctance in giving away responsibilities to allocate infrastructure capacity • RU's resistance in taking over change in responsibility and in business model. • Limited budget and/or acceptance of IMs and RUs to extra installation costs for negotiation-enabling technologies. • Increased price and maintenance of rolling

• Increased transparency in market competition rules and train priority decisions. • Enhanced multimodal integration of the railways for both freight and passenger services. • Alleviate IM's responsibilities in defining traffic rescheduling strategies • Personnel cost reduction for IMs due to decrease in number of dispatchers • Potential IM's business expansion to multimodal transport integrators/coordinators • Decreased RU's operational costs for unused train-seat/km due to improved match with demand trends	stock if additional on-board software/hardware is required for negotiation. • Risk of "system borders" limiting accessibility of trains not equipped with negotiation-enabling technology. • Lack of stakeholder's trust in a new business model especially regarding safety and security • Lack of vision on developing new business processes and roles to enable traffic self-organisation • Negotiation approach requires acceptance and agreements of involved RUs which might have different targets. • Resistance from dispatchers and train controllers in accepting shift to a new traffic management paradigm.

The main strengths listed for rail traffic self-organisation mostly refer to a greater operational flexibility allowing train services to better adapt to customer demand trends and local / specific traffic / infrastructure configurations (scalability) in both nominal and degraded conditions. A relevant advantage identified for a self-organising traffic management is an improved service responsiveness to disturbances thanks to the reduced complexity (hence a more efficient resolution) of the train scheduling problem which refers to a neighbourhood of trains rather than to an entire network as it is customary for centralised approaches. One other main strength mentioned by the respondents is that rail traffic self-organisation will not only facilitate resource information sharing across the multimodal transport network but will allow a more transparent decision process of train priorities while taking into account individual needs of train services.

In contraposition to those strengths, several weaknesses are mentioned by the experts. Such weaknesses mainly relate to the local boundaries considered in the train negotiation process, which might limit identifying globally-optimal traffic strategies and controlling the effect of local decisions on network-wide service performances / capacity. In addition, the train negotiation process might be prone to bias from self-declared importance if not all train services / operators play by the rules. That can not only affect the quality of self-organising traffic strategies but in combination with the competitive structure of the current railway market might prevent train services / operators from reaching a shared consensus in the negotiation process. The potential need of an additional train-to-train communication layer is also considered a weakness of the self-organising approach, because the train negotiation process will depend on the integrity, efficiency and effectiveness of the communication technology.

Many are the opportunities which interviewed experts recognise in rail-traffic self-organisation from the business, legal and research perspectives.

From the business standpoint, a self-organising rail traffic paradigm is found to make the current railway market more attractive to both customers and operators, hence improving the overall competitiveness of the railway mode in line with the EC White paper targets. The main reason for that is that a self-organising rail traffic paradigm can open opportunities for novel customer-centric / on-demand railway business and improve the overall accessibility of the existing market to new and/or smaller operators. One other relevant element is that rail traffic self-organisation can also facilitate the synchronisation with other transport modes and lead to more integrated and attractive multimodal transport network for both passengers and freight. On the other hand, a reduction in railway management costs might be achieved, as IMs will potentially need less personnel for traffic planning / dispatching while the RUs might decrease wastes in train-seat / km thanks to a better match with customer demand trends. In addition, experts also mention potential business expansions for IMs whose role might be upgraded from railway infrastructure managers to integrators / managers of part or the entire multimodal network. The introduction of a self-organisation paradigm is also considered an opportunity to fast-forward the technological / technical enhancements (e.g. digitalisation) of the current railway system, especially for low complexity / low traffic corridors, where the concept could be more easily piloted.

From the legal point of view, experts mention that rail traffic self-organisation will likely improve the balance of traffic management responsibilities, by moving part of IM's decisional roles to RUs. That could potentially lead to an enhanced coordination between traffic planning and operations as well as an increased transparency and equality in both market competition rules and traffic-related decisions.

In terms of research self-organisation could open new streams of dedicated scientific and applied research relative to both methods for effective train negotiation as well as communication and other technologies enabling the deployment of a self-organising rail traffic paradigm.

Opposed to the above reported opportunities, a set of threats are identified for rail traffic self-organisation. From the business point of view, interviewees see potential resistance from both IMs and RUs to additional investments for installing communication technologies and onboard software / hardware necessary for the train negotiation process. At the same time, there might be a lack in stakeholders' trust and vision relative to novel business model and processes. Main reasons could be for instance related to additional safety / security issues such as cybersecurity risks of the communication layer enabling the train negotiation process. Similarly, there might be the risk of creating additional "system borders" which can limit the accessibility on the railway network to trains not equipped with negotiation-enabling technology.

From the legal perspective, both IMs and RUs might be reluctant in accepting changes in the current repartition of traffic management roles, especially regarding potential ambiguities in accident / disruption responsibilities and the substantial changes in traffic controllers' tasks. In addition, experts report the need of potentially long and complex approval procedures for standard processes and data policies enabling train negotiation. Novel rules and regulations will be required and need to be agreed among all involved stakeholders' to provide transparent and effective negotiation process and avoid unclear decision making of train service priorities / strategies.

From the research standpoint, experts mention the threat that future R&D in the field of self-organising rail transport might be compromised in case of technical difficulties in testing / piloting the concept.

2.4 Step changes and recommendations for migrating to self-organising rail traffic operations.

This section provides an outline of the answers given by interviewed experts to questions Q5 and Q6, which are respectively relative to defining critical step-changes and recommendations allowing a potential transition to self-organising rail traffic operations.

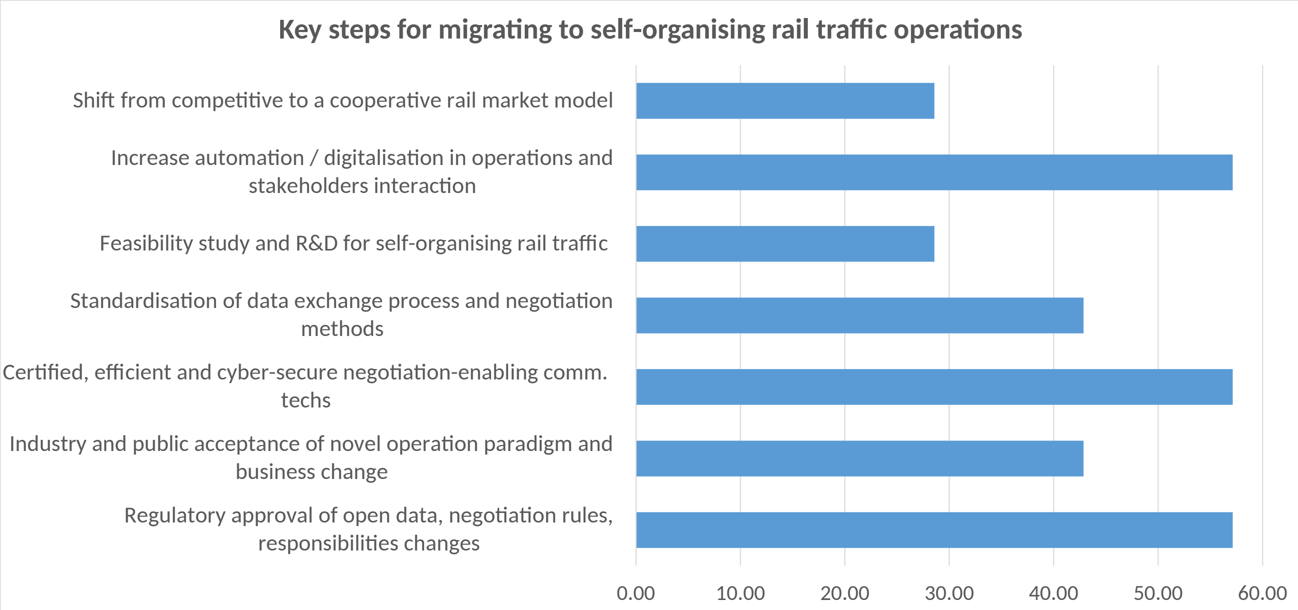


Figure 25. Critical step changes for migrating to self-organising rail traffic

As illustrated in Figure 25, several key changes have been identified as necessary before a self-organisation rail traffic paradigm can be implemented. In line with the outcomes from question Q2 (about the conditions allowing self-organising to overcome current gaps), the majority of the respondents (57%) agree on three relevant steps to be made, namely:

i) A regulatory approval of open data policies, train negotiation rules as well as changes in stakeholders' responsibilities.
ii) The development of a certified, efficient and cyber-secure communication layer to enable train negotiation procedures.
iii) The increase in automation and digitalisation levels of existing railway operations and the stakeholders' interaction processes.

Interviewed experts hence indicate that a shift is required on the regulatory level, with policies for open data, decision-making and stakeholders' responsibilities, as well as on the technological level, with a more digital railway system.

Critical steps are also indicated on the technical level and in terms of public acceptance. A representative portion of the interviewees (42%) finds indeed the need for standardising data exchange processes and train negotiation methods, as well as the acceptance of the novel operational / business paradigms by the industry and the public.

Other key actions to be made also regard a deeper investigation of the self-organising concept as well as changes in the current rail market model. Part of the respondents (29%) answers that a more detailed feasibility study and R&D activities are needed to better understand the impact of rail-traffic self-organisation on the railway business beside train service performance. Also, a shift from the current competitive rail market to a cooperative structure is required to enable an effective negotiation among different train services and operators.

In line with those step-changes, interviewed experts provide a set of recommendations regarding the technical, technological and business / legal areas of the railway system. Such recommendations are found to be consistent with the conditions indicated (in answer to Q2) by the respondents to allow self-organisation overcoming current traffic management gaps versus EC's White paper targets. Specifically, the following recommendations are provided in order of expressed relevance:

- A cost / benefit analysis of the self-organising rail traffic paradigm shall be performed to quantitatively assess impacts on both train service and railway business performances.
- Automation and digitalisation levels shall be progressively increased in current rail traffic management / planning and operational processes as well as in stakeholders' interaction procedures.
- Research and Development activities shall be promoted and performed to identify efficient and effective train negotiation methods and enabling communication technologies.
- Proof-of-concepts of self-organising rail traffic paradigm shall be made either in human-in-the-loop simulation environments or low complexity corridors to evaluate effects on operational procedures and industry/public acceptance.
- A joined action shall be made by the railway and the transport sector to define open data policies for sharing information on services, customers and operators.
- Data relative to customers (both passengers and freight) and operations of other transport modes shall be progressively integrated with existing rail traffic management / planning procedures to foster a flexible and attractive multimodal transport network.

- Round-tables involving the entire public transport sector shall be held to identify potential roles that rail traffic self-organisation can have in investment / development strategies to achieve EC White Paper’s goals.

5 CONCLUSIONS

The research described in this deliverable has three main objectives. The first objective is validating the algorithms developed for describing and forecasting users' travel choices. The second objective is assessing the impact of self-organising traffic management decisions on train delays and users' travel costs, respectively for the single-track line Guingamp-Paimpol, the urban Copenhagen network and the mixed-traffic rail stretch Pioltello-Rovato. The third objective is to provide an analysis of current rail traffic management gaps, potential roles of a self-organising paradigm, and a set of recommendations towards the achievement of the EC White Paper's goals.

The validation of the data-driven demand prediction models shows that an accurate estimation of observed demand trends is achieved for the case of a portion of the Copenhagen rail network.

The assessment of developed rail-traffic management algorithms is performed by applying the integrated SORTEDMOBILITY simulation platform to the three considered case studies for several delay scenarios. Self-organising traffic management is compared versus the centralised approach in terms of total train delays, delay costs and total passenger travel times. Both rail traffic management approaches are benchmarked versus the baseline of trains following the timetabled passage order at interlocking areas. Simulation experiments show that self-organising rail traffic management algorithms can in general perform as well as the centralised approach in significantly reducing train delays with respect to the timetabled train order. When passenger demand is considered, traffic self-organisation seems to slightly increase train delays versus the centralised in in favour of an improvement in passenger travel times. Such benefits in passenger travel times however seem to decrease with high-density traffic (such as the Copenhagen case) and longer dwell times, due to the limited local traffic view of the self-organising approach, whose effect becomes more relevant when dense/complex traffic interactions are considered. These findings support the conclusion that self-organizing rail traffic management can reach similar benefits of centralised systems, while often improving passenger convenience and in general computational complexity. Outcomes show that the developed approach can be effectively used across various types of railway networks, offering a promising alternative to traditional centralized management. Further research is however needed to characterise the influence of traffic density and large delays on general performances of self-organising approaches, to understand the extent of their applicability with respect to centralised traffic management.

An expert survey has been conducted to identify main gaps / limitations of state-of-practice and potential roles that rail traffic self-organisation can have in effectively achieving transport sustainability and competitiveness goals. The main limitations currently stay in: i) the legal / technological barriers for open information sharing within the railways and with other transport modes, as well as ii) the poor digitalisation level together with the current competitive (among RUs) and separated (between IMs and RUs) railway organisation. Those factors are considered to be still a hurdle to migrate towards the strategic EC's vision of a more flexible, attractive and integrated multimodal transport system. A self-organising rail traffic paradigm is considered to help overcoming such gaps if it can fast-forward the processes of railway digitalisation, the approval of policies and technologies for open data sharing and a shift to a cooperative rail market. In that case self-organising traffic management is recognised to improve flexibility of train service to customer demand trends and local traffic / infrastructure conditions both in nominal and degraded conditions. An improved scalability and responsiveness of railway operations can be achieved although rescheduling strategies might only be sub-optimal and prone to bias from self-declared importance (if not all train operators play by the rules). Rail traffic self-organisation is found to be key to open new opportunities to synchronise train planning / management and operations with other transport modes such to foster multimodal integration. That would further contribute to increase attractiveness of the rail transport mode as well as expanding the railway market with an easier accessibility for smaller/new operators. On the other hands, several threats are seen especially in terms of reluctance of the railway industry in accepting changes in the current business model, responsibilities and regulations as well as planning extra investments for installing negotiation-enabling technologies.

Interviewed experts believe that the transition to a self-organising rail traffic paradigm requires at least the approval of policies for open data, train negotiation and business change, as well as the increase of rail digitalisation levels, including the deployment of a certified, cyber-secure communication technology. Before a migration to rail traffic self-organisation is possible, it is recommended that a more detailed research is performed relative to cost/benefit analysis, methods and technologies enabling such a paradigm.

Further progress shall be made in advancing the automation and digitalisation of existing railway operations and stakeholders' interaction procedures. Relevant is however the role of the transport industry which shall initiate joined actions and round-tables to define common strategies, policies and regulations allowing open information sharing and necessary business changes to achieve a flexible and attractive multimodal transport system.

6 REFERENCES

E. Quaglietta. A Microscopic Simulation Model For Supporting The Design Of Railway Systems: Development And Applications. University of Naples Federico II, Italy, 2011.

European Commission, White paper on Transport: Roadmap to a single European transport area – towards a competitive and resource-efficient transport system, Publication Office of the European Union, Luxembourg, March 2011.

F. Rodrigues, On the importance of stationarity, strong baselines and benchmarks in transport prediction problems. In 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC), IEEE, 2023, pp. 4927–4932.

D.V.A. Nguyen, J.V. Flensburg, F. Cerreto, Pascariu B., P. Pellegrini, Lima Azevedo C., Rodrigues F., Large-scale demand prediction in urban rail using multi-graph inductive representation learning, 2024, available online at: https://arxiv.org/pdf/2408.15619

G. Sfeir, F. Rodrigues, R. Seshadri, C. L. Azevedo. Identifying Choice Sets for Public Transport Route Choice Models using Smart-Card data: Generated vs. Empirical Sets. 17th International Conference on Travel Behaviour Research - IATBR 2024, Vienna, Austria, 2024

M. N. Tygesen, F. C. Pereira, and F. Rodrigues, Unboxing the graph: Towards interpretable graph neural networks for transport prediction through neural relational inference. Transportation research part C: emerging technologies, Vol. 146, 2023, p. 103946.

P. Pellegrini, G. Marlière, R. Pesenti, and J. Rodriguez. RECIFE-MILP: an effective MILP-based heuristic for the real-time railway traffic management problem. Intelligent Transportation Systems, IEEE Transactions on, 16(5):2609–2619, 2015.

SORTEDMOBILITY Deliverable 2.2, available online at: https:// https://www.sortedmobility.eu/download, May 2023.

SORTEDMOBILITY Deliverable 2.2, available online at: https:// https://www.sortedmobility.eu/download, August 2023.

SORTEDMOBILITY Deliverable 3.2, available online at: https:// https://www.sortedmobility.eu/download, November 2023.

SORTEDMOBILITY Deliverable 4.2, available online at: https:// https://www.sortedmobility.eu/download, November 2023.

SORTEDMOBILITY Questionnaire, available online at: https://shorturl.at/amHJU, March 2024.

T. Chen and C. Guestrin, XGBoost: A Scalable Tree Boosting System. CoRR, Vol. abs/1603.02754, 2016.

T. Kipf, E. Fetaya, K.-C. Wang, M. Welling, and R. Zemel, Neural Relational Inference for Interacting Systems, 2018.