Evaluation of the delay management potential on a macroscopic level

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Summary

In general, macroscopic models in delay management allow for the optimization of large networks with reasonable computational effort. The main limitations here arise from the aggregated consideration of the infrastructure. In this paper, an evaluation of potential application of macroscopic models for delay management through a real case study is discussed. A macroscopic model is built by applying first a micro-macro transformation on a calibrated microscopic model, to provide an exact calculation of minimum running times and headways. On this macroscopic model, two disruption scenarios are analyzed and solved by using Event Activity Networks, to show the potential benefits and the limitations of delay management. The case study is based on a real railway infrastructure in Switzerland, and it is implemented in LinTim, an opensource software, which allows for an integrated development of both the macroscopic scenario and the delay management solutions.

Keywords: Delay management; EAN; Micro-Macro-approach; Simulation, Optimization

1 Introduction

The task of delay management (DM) is generally to manage the connections between different trains to minimize passengers' inconvenience (delays, missing connections, etc.) when delays occur [1]. The goal is to generate a new, producible timetable as quickly as possible in case of a disruption during operation by means of suitable measures.

In the literature, different models and methods for computer-aided DM can be found (see [1] for a comprehensive review and classification). According to the specific focus, DM models may have different levels of detail in the infrastructure modelling, i.e. typically macroscopic models (see e.g. [2]) or microscopic models (see e.g. [3]).

From a technical perspective, macroscopic models ensure a fast response when the network dimension becomes larger, at the expense of precision. Specifically, it is possible to easily build *Event Activity Networks* (EANs) from macroscopic models, thus allowing for an explicit and quick representation of train schedules and train connections, and the minimization of passenger delays can be solved through fast responsive models, such as those based on Integer Linear Program (ILP) and described in [2].

Microscopic models are instead very precise and therefore very helpful when train movements have to be managed, e.g. in station areas. On the other hand, microscopic models usually do not allow for a fast response in large networks and in most of the cases microscopic tools do not include travel demand information [4].

One of the main research streams is to combine both approaches, with the aim to improve the performances of optimization algorithms for DM. One of the first contributions in this stream has been presented in [5], in which infrastructure capacity constraints have been added to a DM macroscopic model. A bi-level approach has been proposed in [6] and [7]; where microscopic local routings are looped with a macroscopic coordination level.

In the last decade, the idea to directly transform microscopic models into macroscopic, and to conveniently manage the aggregation of the relevant microscopic information, has been pursued, and main applications can be found in the timetabling field (e.g. [8] [9] [10]). Following this approach, the contribution of this paper is a preliminary evaluation of the DM potential of a macroscopic model, based on a micro-macro transformation. A preprocessing micro-macro transformation phase based on [8] is performed to obtain a macroscopic model from a dense microscopic model developed in OpenTrack [11]. The macroscopic model will be then represented through EANs and the DM processes will be managed in the open-source environment LinTim [12]. A real case study of a railway infrastructure in Switzerland is proposed, in which 2 delay scenarios and their related DM solutions are described to show the potential benefits and the limitations of such approach. The paper is structured as follows: Section 2 is dedicated to models' description, namely micro-macro transformation and its specification for DM applications. Section 3 introduces the case study and the delay scenarios. In section 4, the discussion of the results is presented. In section 5, conclusions and further investigations are addressed.

2 Models' description

2.1 The preprocessing phase: Micro-macro transformation

The methodological aspects concerning the information transfer between microscopic and macroscopic models are based on the framework described in [8], from which the main concepts and definitions (e.g. station and pseudo-stations, route, block section, blocking time stairway, headway) are adapted in this study. Thus, the specific adaptations made for enabling the DM models will be here presented.

A micro-macro transformation is generally adopted to find a trade-off between required accuracy and manageable complexity. At infrastructure level, a microscopic rail network is usually represented by an oriented graph G = (V,L), where V denotes the set of vertices and L the set of edges [13]. The micro-macro transformation can be conveniently performed by fixing a set of (potential) routes R in the graph G = (V,L) for the planned lines and the related train types. The result is a macroscopic rail network RH = (S, M) made of station nodes S and edges M that connect these station nodes, according to R. It is important to consider for the following discussion that, by fixing the routes set R, the interactions between trains to consider will be much less than those computed directly on the infrastructure topology, i.e. a selected number of interactions vs. all possible interactions. On the other hand, a potential optimization model based on such a macroscopic network, e.g. a rescheduling model, will not consider alternative train routes (rerouting) during the search for new solutions, thus it will adopt only reordering and retiming actions for the generation of new timetable plans. This could be a particularly limiting factor in station areas.

According to [8], the feasibility of rail operation is achieved:

- at a microscopic level when the blocking time stairways of two trains running on a shared infrastructure (i.e. a part of their routes in common) do not overlap each other.
- at a macroscopic level when a minimum headway time between each two succeeding trains running on the same infrastructure is respected.

The goal of a micro-macro transformation is to define conflict-free microscopic blocking time stairways to be converted into minimum headways in a macroscopic environment. By generating a new timetable solution in the macroscopic level (e.g., through an optimization model) with respect to these minimum headway times, conflict-free conditions in the microscopic level are also respected. Other information that are transferred into a macroscopic model are the minimum running times and time discretization. This last for our purpose is not necessary because the LinTim environment accepts the 1 second accuracy, which is a standard in microscopic environment.

To solve the DM problem, headway times must be computed. Specifically, to find solutions that include train reordering, minimum headways between pairs of trains must be computed in the original train order (planned conditions) and in the inverse order (Swapped condition). For a clear understanding, let assume that Train 1 and Train 2 are two trains respectively arriving and departing to/from a given station *Stat* (see Figure 1 for reference). The infrastructure topology represented on the x-axis shows that most of the infrastructure is shared by the two trains, and train crossing is possible only in a specific double track section of the infrastructure and at station *Stat*. The following train sequences and related minimum headways are possible and must be evaluated: Train 1 arrives before Train 2 departs and Train 2 departs before Train 1 arrives.

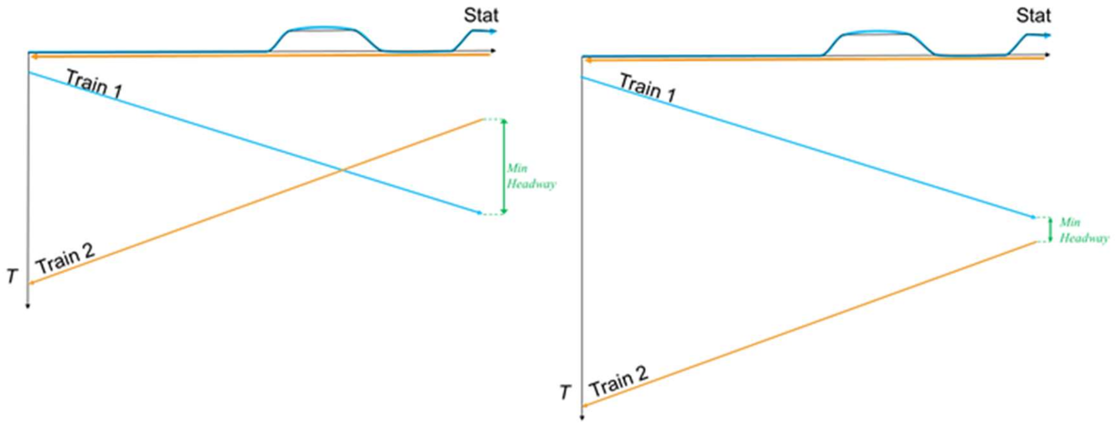


Figure 1. Schematic representation of possible train sequences and related minimum headways. .

2.2 Delay management through Event Activity Networks

Solving a DM problem means finding a new configuration of rail traffic (i.e. retiming, reordering, rerouting of trains) in order to minimize passenger delay, preserves the connections, and in general minimizes the inconveniences for passengers. In the real operation, small computing times for solving delay problems are required for an effective and quick intervention, and macroscopic environments are used because they allow to solve DM problems in times that are compatible (in the order of 1-3 minutes) with the railway operation and the need of the travelling users. Train routes and their interdependencies can be modeled as a set of events (e.g. departure, arrival) and activities (e.g. run, wait, headway, change), thus the rail traffic can be represented by an Event-Activity Network (EAN).

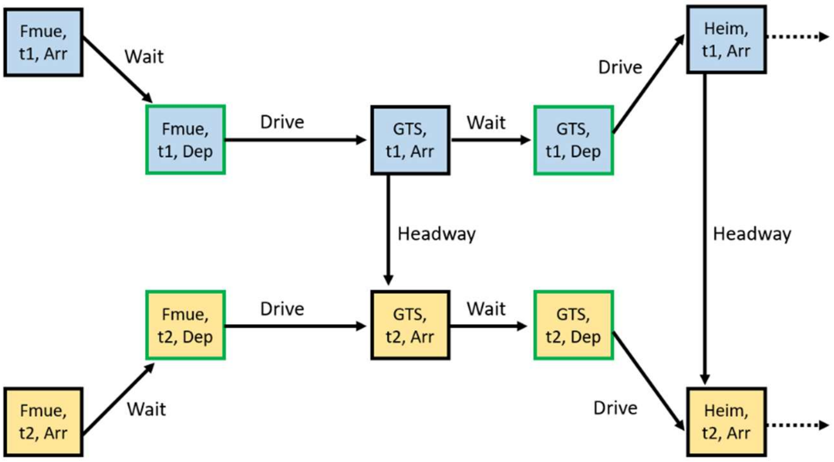


Figure 2. Example of Event-Activity Network describing the two consecutive trains that run in the same direction within the station area of Lucerne.

As also shown in [2] the EAN is a graph where the events are modeled as vertices and the activities as directed edges. It is used in public transportation for timetables development, connections representation and in DM. In figure 2 a schematic representation of the EAN referred to a part of the following case study (see figure 3) is shown as example.

In this paper, an EAN for DM purposes and specifically designed for rail operation is presented. More specifically, let RH = (S, M) be a macroscopic network of the rail infrastructure and T be a set of trains operating on it. The set of all trains that stop at station $s \in S$ is denoted by T (s). The event-activity network associated to RH, $N_{RH} = (E, A)$ consists of the set of events $E = E_{arr} \cup E_{dep}$, and a set of directed edges called activities $A \subset E \times E$. An arrival event (s, t, arr) represents the arrival of a train $t \in T(s)$ at a station s, and a departure event (s, t, dep) represents the departure of train $t \in T(s)$ at station s. The set of activities includes the following relevant subsets:

- A_{drive} (driving activities) are of type $((s_1,t,dep), (s_2,t,arr))$ for some $(s_1, s_2) \in S$, $t \in T(s_1) \cap T(s_2)$ and represent a train t driving from station s_1 to the next station s_2.
- A_{wait} (waiting activities) are of type $((s,t,arr), (s,t,dep))$ for some $s \in S$, $t \in T(s)$ and represent the dwelling activity of train t at station s,
- A_{head} (headway activities) are of type $((s, t_1, dep/arr), (s, t_2, dep/arr))$ for some $s \in S$, $t_1, t_2 \in T(s)$ and represent the sequence between two events (*dep/arr*) of two different trains t_1, t_2 at station s.

Activities can also model passenger transfers (changing activities) and the train operations between the last event of a train run and the first event of the following one (turn-around activities).

As previously mentioned, headway activities usually come in pairs (*i, j*) and (*j, i*), i.e. the planned train order configuration and its opposite (i.e. headway swap), to allow the delay management model for a possible new configuration of arrivals and departures at a given station or pseudo-station (i.e. train reordering). Pseudo-stations ([8]) identify the operating points of a given infrastructure. These are modeled in the macroscopic network as "stations with no platform", i.e. where boarding and alighting of passengers is not permitted and on which operations like convergence, divergence and crossing can be conveniently modeled.

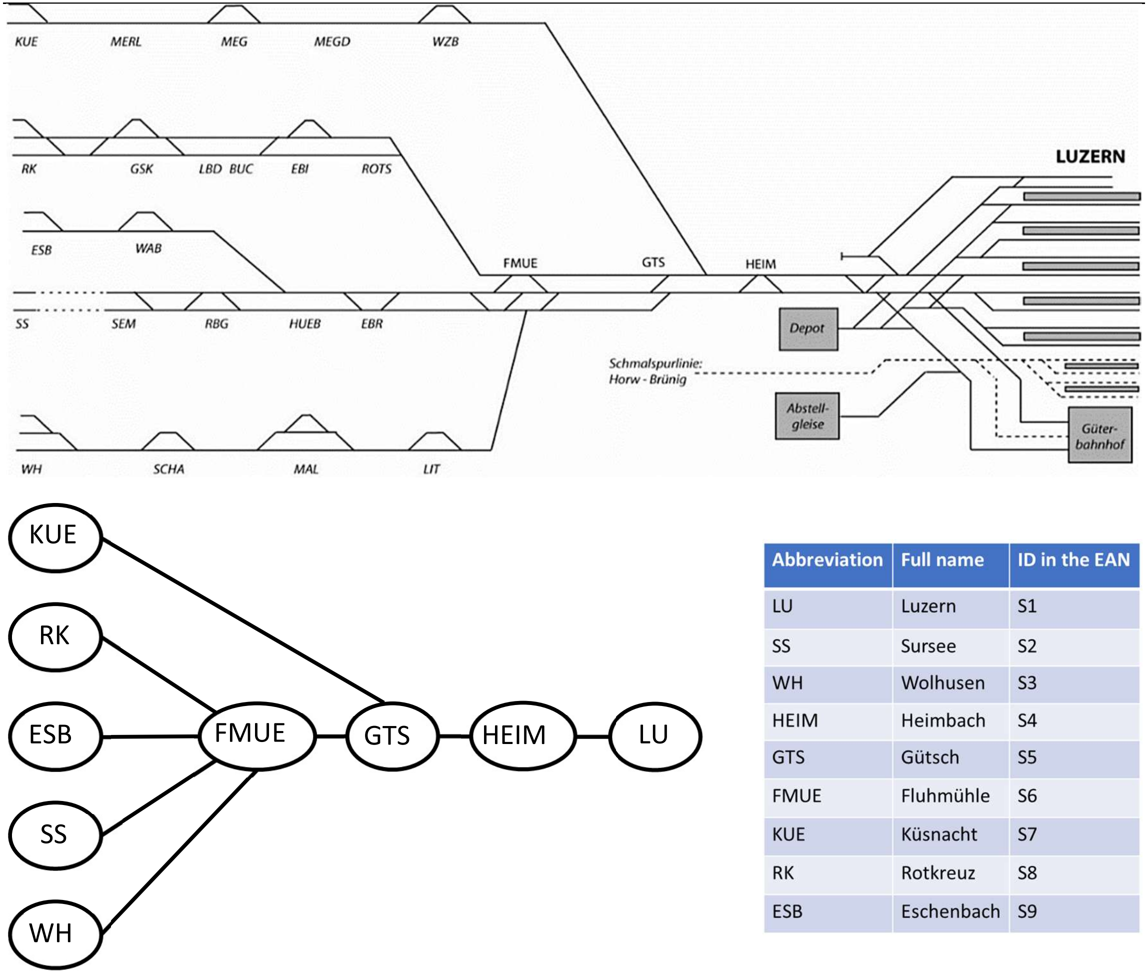
In EANs, passenger information can be also integrated. Specifically, Origins and Destinations of passenger flows, as well as their connections at stations, must be based on the same stations set $S \in RH$ (e.g., passengers traveling from s_1 to s_2 with a connection in s_3) that is used for identifying the train paths. Pseudo-stations are not considered in passenger trips and connections, even if they are included in the set of station S.

By assigning a timetable to the events (i.e. departure times and arrival times), the duration of each activity is also defined. In this way, EANs can model train routes together with passenger routes, and compute route delays and cumulative delays both for trains and for passengers, when delay times are introduced.

To solve the DM problem with EAN, information on minimum times for A_{drive}, A_{wait} and A_{head} must be also introduced. These minimum times will be treated as constraints in the DM problem to ensure a feasible and conflict free solution. In this paper, we solve the DM model by considering consider methods based on *propagation,* in which a *waiting time rule* is applied, and an Integer Linear Programing – ILP based method (for a full description of the models, please refer to [2]). The propagation method is tested with threshold values of 0 (i.e., *no wait rule*) and 800 seconds, with and without headway swap option. In propagation-based methods, the given initial delays are applied and then transmitted over the subsequent events and activities in the EAN. An activity may include some buffer time, which reduces the transmitted delay. In other words, an event time becomes fixed after being visited (due to the topological sorting, all events taking place earlier have been fixed before) and its successor events (targets of outgoing activities) are delayed as much as necessary to fulfill the lower bound of the time duration for the respective activity. When a *waiting time rule* is applied, change activities are cut off (so that delays do not propagate along them, since the constraints on the minimum time for the related transfers are removed) after a maximum waiting time has passed: if the target event of a change activity is delayed by more than the specified threshold value, then this change activity is not respected anymore. As mentioned, we also consider the case where precedence orders and related headway constraints can be swapped. In fact, in some cases the train that was originally scheduled first is so late that the successive scheduled train can go first, without affecting/being affected by the delayed train. The ILP is based upon the same propagation constraints. Additionally, it includes mutually exclusive constraints for headways swaps and change activities cut-off constraints. When change activities are cut off, penalties are added to the cost function, together with a weighted sum of the delays that account for the passenger flow.

3 Case study: Lucerne station and surroundings

For a complete understanding of the proposed DM models, the EAN representation and the micro macro transformation, a case study based on a real-world scenario has been taken as reference. The selected area is the station of Lucerne, represented in figure 3, with its operating points Fluhmühle (FMUE), Gütsch (GTS) and Heimbach (Heim). The infrastructures diverge towards different directions, i.e. to Wolhusen (WH), to Sursee (SS), to Eschenbach (ESB), to Rotkreuz (RK), and to Küssnacht (KUE). The data on trains, train runs, and the timetable are also taken from the real world, and provided by SBB, the major rail company in Switzerland. This information has been included in a microscopic simulation environment which is constantly updated and tested. The micro simulation scenario consists of ca. 1840 nodes. There are 140 station nodes, which do not include nodes belonging to the station areas; 93 station nodes have platforms for passengers' boarding and alighting and the remaining nodes are pseudo-stations. The case study here presented consists of overall 47 stations incl. operating points. The rail services included in the whole simulation scenario are local trains (S-Bahn), interregional (IR), regional express (RE), intercity (IC) and Eurocity (EC), whose main difference is the stopping pattern and the consequent minimum travel time between planned stops. There are currently ca. 580 daily trains that stop in Luzern from 4 am to 1 am of the day after, including freight trains.



Abbreviation	Full name	ID in the EAN
LU	Luzern	S1
SS	Sursee	S2
WH	Wolhusen	S3
HEIM	Heimbach	S4
GTS	Gütsch	S5
FMUE	Fluhmühle	S6
KUE	Küsnacht	S7
RK	Rotkreuz	S8
ESB	Eschenbach	S9

Fig. 3. Schematic representation of the infrastructure network topology related to the station area of Lucerne (top, source: [14]) and the considered macroscopic network obtained after the micro-macro transformation (bottom). A table reporting the relevant station IDs in the EAN has been included for reference.

In peak hours the station of Lucerne manages ca. 20 train per hour per direction. The delay scenarios have been built within a 45-min time interval, from 9:45 to 10:30. All the trains that partially or completely operate in this time interval have been considered and their routes have been fixed according to the planned ones. The micro-macro transformation described in [8] has been therefore performed to obtain a macroscopic network, and for our purposes we have also included the pseudo-stations. The passenger demand, which is used for evaluating the cost function to be minimized through the optimization models, has been calculated by matching the data on the average train occupancy rate calculated on single routes and on an annual basis, and reported in the

2017 Nationwide Passenger Traffic Model[1], with the capacity of the single trains in the reference scenario available on OpenTrack. The train change rate, which is required to estimate the number of transit passengers (i.e. connections) was estimated on an empirical basis to be about 1/3 of the previously derived demand.

3.1 The Delay Management models

As previously mentioned, propagation methods with a waiting time rule and an Integer Linear Program (ILP) are implemented in this case study. We refer to the propagation-based methods with P, to the headway swap option with S, to the threshold values for the waiting time rules with just the numerical value in seconds and to the Integer Linear Programming based method with ILP. Hence the employed models are P0, PS0, P800, PS800 and ILP. The performances will be evaluated through aggregated indicators as the average passenger delay (referred to as "APD" below) and the average event delay ("AED" below), to have a reference to the passenger and to the train perspective respectively. The EAN in planned conditions, i.e. without delays, is shown in Figure 4; for the sake of a clear visualization, it has been restricted to the three affected trains only.

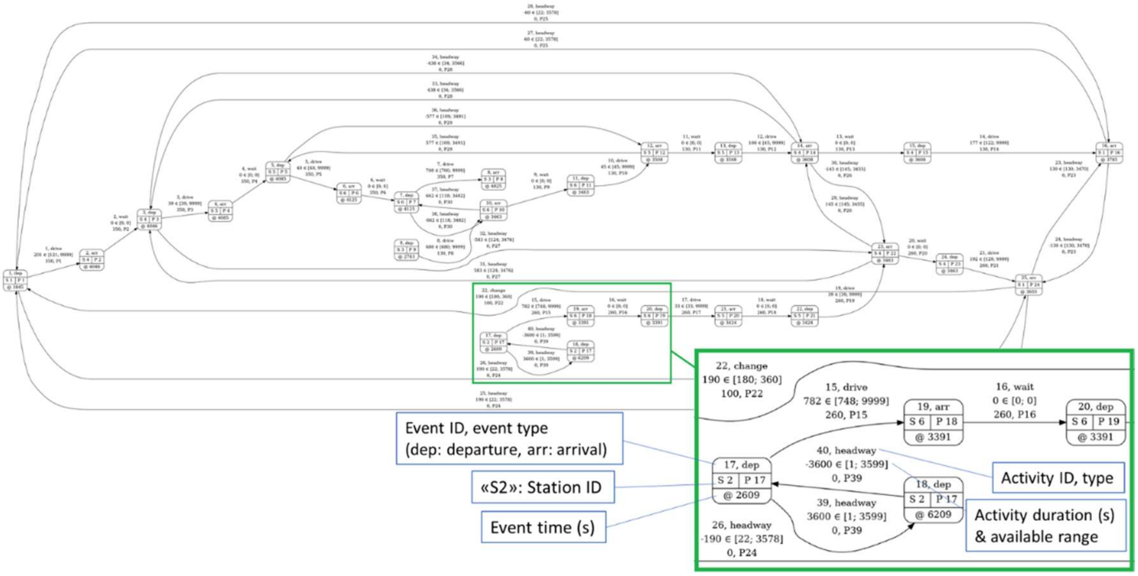


Figure 4. EAN of the planned conditions for the affected trains in the delay scenarios. Highlighted in the green frame, the legend of events and activities characteristics.

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[1] National Passenger Transport Model 2017 for public transport in binary format (VISUM format). Available at https://opendata.swiss/en/dataset/kenngrossenmatrizen-2017/resource/654a30e8-ecc2-4810-8d49-1058dfc91510

3.2 Delay scenario 1: D600

The first scenario supposes a 600 second primary delay of the InterRegio train coming from Geneve airport directed to Luzern via Sursee (train 2511). This affects the connection with the RegioExpress train directed to Wolhusen (train 4466) and generates a conflict in the operating point of Heimbach (Heim) with the route of the RegioExpress coming from Wolhusen (train 4463), with consequent secondary delays on its operation.

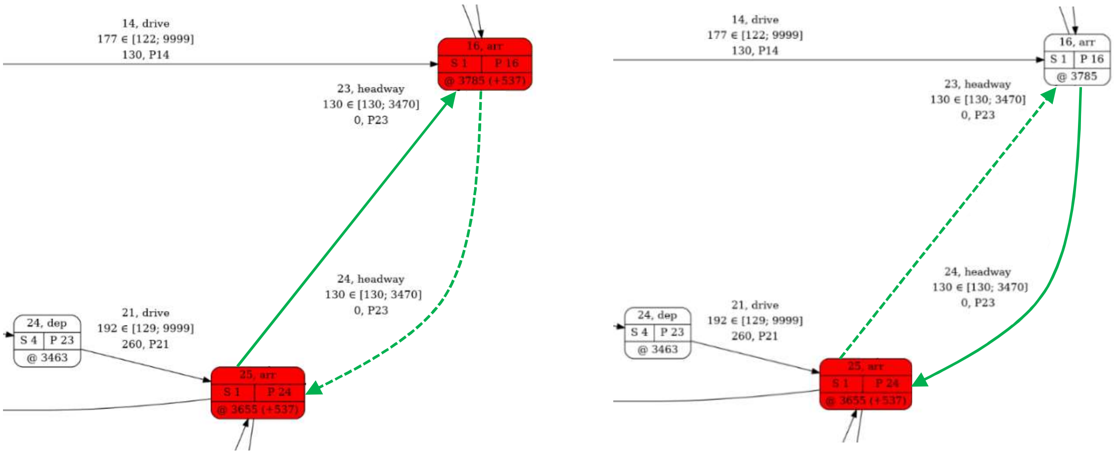

Figure 5. Delay propagation with (right) and without (left) headway swap for train 4463 and 2511 arriving in Lucerne in scenario 1. In round brackets, the delays in seconds. The two headway alternatives for the events "25" and "16" are in green; the continuous arrow marks the chosen option.

In figure 5 a part of the EAN related to the trains 4463 and 2511 is highlighted. The minimum headway time for both precedence orders is 130 seconds and the event "16, arrival" (i.e. train 4463 arrival at the station of Lucerne) is scheduled 130 seconds after the event "25, arrival" (i.e. train 2511 arrival at the station of Lucerne).

Without swapping, the 537 seconds delay on event 25 is propagated to event 16, also because there is no buffer time on the specific headway activity at issue. The headway swap implies that event 16 can take place at its originally scheduled time, i.e. 3785 seconds (ca. 10:03 AM; "0" second has been set to 9:00AM), this time before the delayed event 25, which remains unchanged at 3655+537 = 4192 seconds (10:09 AM). This swap is feasible since the minimum headway time for the inverted order is respected (4192-3785= 407 > 130). Table 1 reports the aggregated output APD and AED for the tested methods. ILP and both the propagate methods showed an example of headway swap when the option has been enabled, as illustrated in the EAN in figure 5.

Table 1: Results from the LinTim solvers in Delay Scenario 1.

Method	APD (s)	AED(s)
P0	970	180.2
PS0	697	**21.5**
P800	488	189.2
PS800	**379**	167.7
ILP	**379**	167.7

The solution has been verified on OpenTrack, which confirmed the conflict free conditions, with very small differences, ca. 2 seconds, for what concerns the headways and the running times. This also confirms the findings in [8] on the goodness of the approach and extends its use for DM scopes.

3.3 Delay scenario 2: Mix-UD

The second delay scenario considers 8 initial delays on different activities (change activities excluded), which have been randomly generated from a uniform distribution. For reference, the main part of the EAN related to this case is highlighted in figure 6. Considering this example with the propagate methods, event “25, arrival” (i.e. at Lucerne, train 2511), which is the source event of the change activity that ends at event “1 departure” (i.e. at Lucerne train 4466), is delayed of 746 seconds.

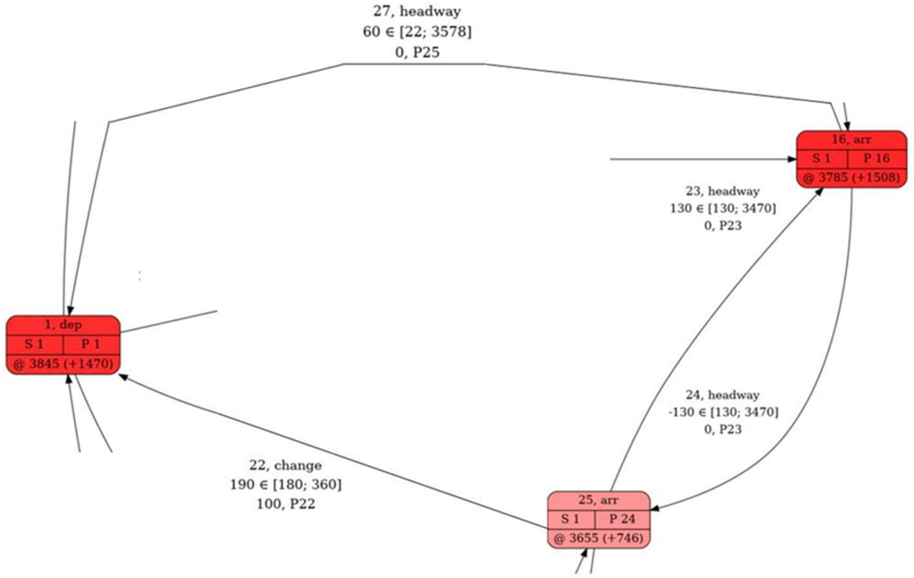

Figure 6. Part of the EAN resulting from delay scenario 2.

On the other hand, event 1 has a delay of 1470 seconds. In this specific case, the delay of event 1 comes headway activity which cannot be swapped (P0 and P800 have no headway swap option). Hence, using both the methods, event 1 is more delayed than event 25 and the transfer can still occur since it would last more than scheduled. In fact, the upper time bound for a change activity is generally considered only at timetabling stage. When the headway swap option is available, it is possible for event 1 to depart on time, while the same does not happen for event 25, and therefore the no-wait rule (with swap option, PS0) cuts the change activity off. Thanks to the swap possibility, PS800 propagates a lower delay to event 1, specifically from the change activity (departure 1, delay of 736 seconds, under the 800 seconds threshold value). For generating the initial delays, the specified range is from 0 to 720 seconds, and the resulting delays are between 131 and 522 seconds. In Table 2 the APD and the AED for this delay scenario are reported. With no possibility to swap headway constraints, the propagate methods P0 and P800 delivered the same results, even if the maximum waiting time is different. In this case it is possible to see how setting a no-wait rule does not automatically mean to cut all change activities.

Once again, PS800 and the ILP minimized the passenger delay, while PS0 the event delay. The microscopic simulation of the solution through OpenTrack confirmed the conflict free conditions and the small differences with the macroscopic model, as in the previous delay scenario.

Table 2: Results from the LinTim solvers in Delay Scenario 2.

Method	APD (s)	AED(s)
P0	1473	873
PS0	1203	**412**
P800	1473	873
PS800	**1071**	639
ILP	**1071**	639

4 Discussion of the results

The DM of the delayed trains has been here performed with the use of EANs and of a macroscopic model, which has been fed with microscopic data on headways and running times. The software LinTim offered the opportunity to both build the EAN from the macroscopic network RH and to develop the DM solutions for the delay scenarios. Overall, in terms of passenger delay, the ILP and PS800 perform better than the others in both the tested scenarios, with 379 seconds and 1071 seconds, in the first (D600) and second (Mix-UD) delay scenario respectively.

P0 returned the worst values: 970 seconds for D600 and 1473 seconds for Mix-UD; in scenario Mix-UD, P800 returned the same result as P0. It is worth observing the effects of enabling the headway swap option. A headway swap has the meaning of changing the sequence of two trains. This is of course only possible, if the real time conditions allow, from the safety point of view, to re-order the train routes. As main impact, it reduces the secondary delay of the first train in the new train sequence and keeps the train delay low. This results in a drastic improvement of the average passenger and event delays for both the propagation methods. The fact that PS800 achieved the lowest APD together with the ILP indicates that, in these scenarios, deleting connections (i.e. deleting change activities) has a more penalizing effect than waiting and propagating the delay.

The event delay has been also analyzed to understand the effects of DM from the operator's perspective. In both the delay scenarios, the minimum event delay has been achieved by PS0, the no-wait rule with swap option. Keeping a change activity can be beneficial to passenger delay, but it also means to allow delays to propagate over the subsequent events. As a matter of fact, the AED has risen with the higher maximum waiting time in almost all cases. In the first scenario, the solution provided by P800 results in the highest AED, with 189 s, while PS0 the returned a result of 21 s, and P0 a still lower value of 180 s. The ILP achieved a value of 167 s, which is lower than P800 but still far higher than the value from PS0; it is relevant to remark here that the cost function of the ILP aims at minimizing passenger delay only. About the second scenario, the pattern is the same, with the difference that P0 and P800 returned the same values.

The computation times for all the tested algorithms doesn't exceed 4 seconds on a commercial laptop (4-cores Intel processor and 8 GB RAM). This is a promising premise for future applications in real operation, considering the decisional phase, the conversion into the so-called disposition timetables and the communication to train drivers and the station managers. It is also worth to note that these values are reachable because of the integrated framework used and depend on the numbers of trains and passenger connections considered.

As a general discussion, the authors want also to remark that, following the DM problem classification made by [1], in the last years the number of problems linked with DM has grown and the distinction between their solutions is often blended. Not only dispatchers are in charge to decide, in the short term and in each case, how the operation must continue. Rather, a modified timetable with vehicle and personnel deployment plan, etc., adapted to the situation is often required. Nevertheless, the distinction made in [1] between DM problems and Real Time Rescheduling (RTR) models can be a reading key for developing an interesting research discussion.

As previously mentioned, a possible limitation of its use may be given by fixing the train routes for managing less headways. This, in practice, limits the use of LinTim to the adoption of retiming and reordering options, while the train rerouting actions cannot be performed automatically. The train rerouting action can be ideally managed with a preprocessing phase where the headways of all (or some of) the rerouting options are computed; this results in a set of possible EANs. Through an external optimization routine, it can be possible to explore the availability of new train routes that reduce the conflicts. Then, in a subsequent step, the retiming and reordering processes act as a fine tuning of the chosen routing option. This will most probably impact the computation speed, but will increase the solution search area and thus the impact of the resulting solution.

5 Conclusion

In this paper we considered several models of DM implemented in LinTim on a macroscopic level. The optimization potential of DM has been measured with respect to passenger and event delay. Various disruption scenarios in a real case study of a railway infrastructure in Switzerland have been analyzed. The example is implemented on a microscopic level in the commercial software OpenTrack. Using a micro-macro approach, a macroscopic model is first generated. On this macroscopic model, different delay scenarios are analyzed and solved through EANs within the LinTim environment. The micro-macro approach subsequently allows the calculated measures (e.g., new timetables) to be translated back into the microscopic model. The measures obtained from LinTim are then validated in OpenTrack. In this paper two main achievements have been reached. First, a real-world scenario has been used to show the potential of DM. Second, the quality of the measures generated by the macroscopic model has been enhanced with the help of the micro-macro approach. Future works in this field will focus on expanding the methodology on more complex real-world scenarios, with more trains, tracks, stations, and passengers. This will also include further works to extend the capabilities of the micro-macro transformation and to consider rerouting options in the EAN modeling. Another interesting direction is the integration of the proposed approach with vehicle and crew scheduling, which allow to ensure the feasibility of dispositions in case of disruptions and to optimize the operating costs.

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