Redirecting Passengers and Reallocating Capacities during Incidents in Public Transport

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ABSTRACT

The attractiveness of a system is directly connected to its reliability. The more reliable a system is the more attractive it is for its (potential) users. In public transport this means that more people shift to public means of transport when it gets more reliable. One way to improve their reliability is to mitigate the negative effects of incidents on the public transport service and on its users.

This paper introduces a new passenger centric incident management method to mitigate negative effects of incidents. Incidents such as traffic accidents and congestion, ambulance deployment, technical failures and similar events cause service cancellations and delays which disrupt the planned trips of passengers. By redirecting affected passengers onto alternative paths whilst considering capacities to avoid secondary incidents lead to a significant reduction of delays.

An additional reduction can be gained by reallocating vacant capacities onto desired alternative paths to support the redirection of passengers logistically. A numerical example is presented, showing the positive effects of the here presented passenger centric method through redirecting passengers and reallocating capacities. These are the first steps towards an optimal solution to passenger centric incident management in public transport.

Keywords: Public Transport, Incident Management, Disruption, Passenger centric

INTRODUCTION

Improving a system's reliability is an effective way to increase its attractiveness to (potential) users. In public transport (PuT), the improvement of a system's reliability can motivate people to shift from private means of transport to PuT modes (e.g. bus, metro) (*1*, *2*).

Mitigating the negative impacts of incidents on passengers affected by such is a possible way. Incidents occur in PuT systems every day. They are understood here as unplanned events such as traffic accident or congestion, ambulance deployments, technical failures, passenger falls or similar events, which disrupt the PuT service. Negative impacts which are caused by such incidents are service cancellations and delays which inconvenience the passengers and cater for longer and unreliable travel times.

The dispatchers working in operators control centers (OCCs) of PuT operators are the main actors of incident management today. They monitor and organize the PuT service and take measures to mitigate the negative impact of incidents. They temporarily reroute PuT lines, dispatch extra vehicles, hold vehicles at stops and use other dispositive measures to dissolve an incident and return the service to normal operation. Moreover, most of these measures were examined in research to find optimal ways to execute them, an overview of such investigations is given by (*1*). All these measures however focus on the supply side of PuT operations, less attention was given to passenger centric approaches to incident management. Most of the investigations which have been done so far focus on major disruptions on rail services (*3*–*6*).

Therefore, the work presented here introduces a passenger centric incident management method (PCIM) to react to any kind of incident in an urban PuT networks. Urban PuT networks are often dense and there are many paths from a certain origin to destination. By redirecting passengers affected by an incident onto unutilized capacities of alternative paths, the delay of affected passengers can be reduced. It is crucial to do this without exceeding these unutilized capacities to avoid secondary incidents.

Moreover, an additional reduction of the affected passengers' delay is achieved by reallocating unutilized capacities onto desired alternative paths to temporarily extend their capacities; thereby more affected passengers can be redirected on these alternative paths without exceeding their capacities.

Another characteristic of urban PuT systems is that they consist not only of rail bounded services like metros, but also of road bounded services such as busses. In large cities the bus network is mostly dense and plays a major role in the cities' PuT. However, most existing investigations seem to be focused on rail bound services, therefore, this work investigates the effects of the PCIM on road bound services.

Furthermore, it is tested in a futuristic mobility concept of a dynamic autonomous road transit (DART), which is under development at TUM CREATE in Singapore (*7*). Its modular and autonomous setup makes it ideal for capacity reallocations. This paper shows that redirecting affected passengers caters for a reduction in delay and that this effect is even further improved by the reallocation of capacities.

STATE-OF-THE-ART ANALYSIS

The state-of-the-art analysis is subdivided into two sections. The first section is about the supply centric side of incident management in PuT, which focuses on the OCC's perspective of incidents. The second section is about the passenger centric side of incident management in PuT and therefore deals with the passenger perspective of incidents.

Supply Centric Incident Management

In practice, the dispatchers in OCCs are the main actors in incident management in PuT. They monitor the service with the help of controlling software which compare the real-time PuT vehicle locations with their respective schedule to detect deviations from it (*8*). If any deviation occurs, the dispatchers communicate with the PuT drivers, like bus drivers, to work against it. In case of an incident, it is usually a PuT driver who is first on site and notices the incident. Whenever a PuT driver encounters an incident, he/she reports it to the OCC. A dispatcher assesses the incident situation based on the information from the driver as well as from the aforementioned software. It is the dispatchers' task to not only return the service back to the schedule but also to cater for the dissolution of the incident. To do so, the dispatcher calls, the police, the fire department, ambulances or towing services, depending on the location, kind, and severity of the incident. To readjust the service to schedule, the dispatchers have several dispatching measures at hand. Visits to six different OCCs of urban PuT systems in Germany and Singapore revealed that rerouting bus lines, deploying extra buses, holding vehicles, and let vehicles deadhead are the most common control strategies in urban PuT. Many of which have been also investigated and optimized in the literature (*1*).

(*9)* divide these strategies into three categories: Station control, inter station control and other strategies. The station control category describes the strategies holding and stop skipping such as deadheading, short turning and expressing since they either take place at stops or alter the number of served stops. Headways can be readjusted to the schedule by PuT drivers extending their dwelling times at stops or skipping stops. (*10)* for instance evaluated several bus holding strategies in the dynamic transit simulation model BusMezzo regarding passenger waiting times and service reliability. The combination of deadheading, expressing, and holding was examined by (*11)*, who developed a heuristic algorithm to minimize the overall waiting time of passengers. (*12)* had the objective of minimizing the total travel time with the combination of holding and stops-skipping. (*13)* combined holding with speed control, which is a kind of inter station control strategy. PuT vehicles speed up or slow down depending on whether they are ahead or behind the desired headway of their preceding and following PuT vehicle. Another inter station control strategy is traffic signal prioritization for PuT vehicles which caters for less waiting time of PuT vehicles at traffic signaled intersections (*14)*. Under the category of other strategies fall dispatching extra PuT vehicles or split and extend PuT vehicles. (*15)* for instance describes the delay recovery strategies of removing a train or adding a gap train in the context of metro services in London. All these works have in common that they are focus on the supply side. Even though they have the aim to improve the service for the passengers the actions are taken focusing on the supply and are hence supply centric.

Passenger Centric Incident Management

In addition to supply centric control strategies, there are passenger centric strategies which take not only the movements of the supply into account but also the behavior of the demand side, hence the passengers. Especially in recent years, there have been several investigations about passenger centric approaches in incident management:

(*3*) coupled a rolling stock rescheduling model with a passengers' assignment model. Passengers affected by a major railway disruption are advised to take a certain route within the railway network to avoid overcrowding. This was then fed back to the rescheduling model to readjust capacities if possible. (*4*) presents a multi-commodity flow model with an event-activity network to find optimal alternative paths for affected passengers in the event of a railway disruption. (*5*) also developed an activity event network to efficiently find alternative trains for passengers affected by train cancelations or delays. (*6)* shows that informing affected passengers in the advance or at the point of time at which an incident occurs decreases the travel time compared to a scenario in which passengers only learn about a disruption once they encounter an affected service.

All these mentioned investigations have in common that they have the objective to reduce the overall travel time of passengers affected by disruptions in railway services. They conclude that influencing affected passengers' paths reduces the delay in case of a disruption.

However, all these passenger centric investigations concentrate on railway services, which raises the question about the effect of passenger redirection in the event of an incident in an urban PuT network. Urban PuT networks have different characteristics compared to such investigated railway networks. Urban networks are rather dense which caters for many possible paths for certain origin-destinations (OD) relation. Hence, it provides also for many alternative paths in case of an incident. Incidents mostly affect one or a few PuT lines, keeping most of the PuT network functional. Additionally, urban PuT networks are intermodal, they often consist of a combination of rail services, like metro lines, and road services such as bus services. Especially, road services have a high flexibility when it comes to control strategies.

They can be deployed anywhere in the road network which has a higher density than the PuT network of a city and can easily be rerouted around an incident site.

Moreover, the headways in urban PuT are shorter compared to regional railway service. The higher flexibility of urban PuT networks makes it also easier to reallocate capacities in the event of an incident. The visits to OCCs revealed that the deployment of an extra bus or on demand services, like taxis, are often used to cover capacity shortages during incidents. In some cases, buses are withdrawn from lines with low demand to increase the capacity of affected lines during incidents. By coupling this reallocation of capacities with redirecting affected passengers could lead to an optimized passenger centric solution in incident scenarios.

Moreover, autonomous PuT concepts like the aforementioned DART with its modular setup could even further improve a passenger centric respond to incidents. The DART is an autonomous and modular PuT mode. Low demand feeder lines are served by one to three modules which couple to serve together; it can go up to ten modules for high demand trunk lines (*7)*. In the event of an incident it would be possible to withdraw modules from lower demand lines, as it is done today with busses but without the negative effect of changing the headway of these lines. This is because a line is served by runs of more than one module. Solely the capacity in forms of withdrawn modules will be reduced. These modules can then increase the capacities on the PuT lines on which the affected passengers are redirected.

It is therefore this paper's goal to evaluate the effects of redirecting passengers in PuT networks of road bounded modes during an incident. Additionally, to evaluate the PCIM's improved effects in the combination with the reallocation of capacities.

METHODOLOGY

$$MIN \sum\nolimits_{affected\ passengers} (tt_{actual} - tt_{planned}) \qquad (1)$$

Where:

tt_{actual} = the actual travel time of affected passengers
$tt_{planned}$ = the planned travel time of affected passengers

The main objective of the here presented approach is to minimize the overall delay of passengers affected by an incident; implies to minimize the gap between the planned travel time and the actual travel time of all passengers affected by a certain incident (**Equation 1**). The here presented approach to this optimization problem is two-fold: redirection of passengers and reallocation of capacities. The first part finds a redirection strategy to utilize the remaining capacity of the network by redirecting affected passengers onto it. The second part supports the first one by extending the capacities of the most effective alternative paths through the reallocation of dispensable capacities. By having an increased supply on these alternative paths, more affected passengers can be redirected onto these without exceeding the alternative paths' capacities. Hence, the combination of the redirection of passengers and the reallocation of capacities leads to a new and better solution than the redirection of passengers on its own.

Redirection of Passengers

In the first part the passenger side is investigated. The focus lies here on the passengers whose planned trip is directly affected by the incident. To identify these passengers, travel data needs to be analyzed, which is the first step in the here introduced algorithm of the PCIM (**Figure 1**). Different sources can serve as input of travel data, depending on their availability. (*4)* for instance, uses sold train tickets as travel data input, other sources are manual random counts, automatic passenger counts or smartcard data (*16, 17)*.

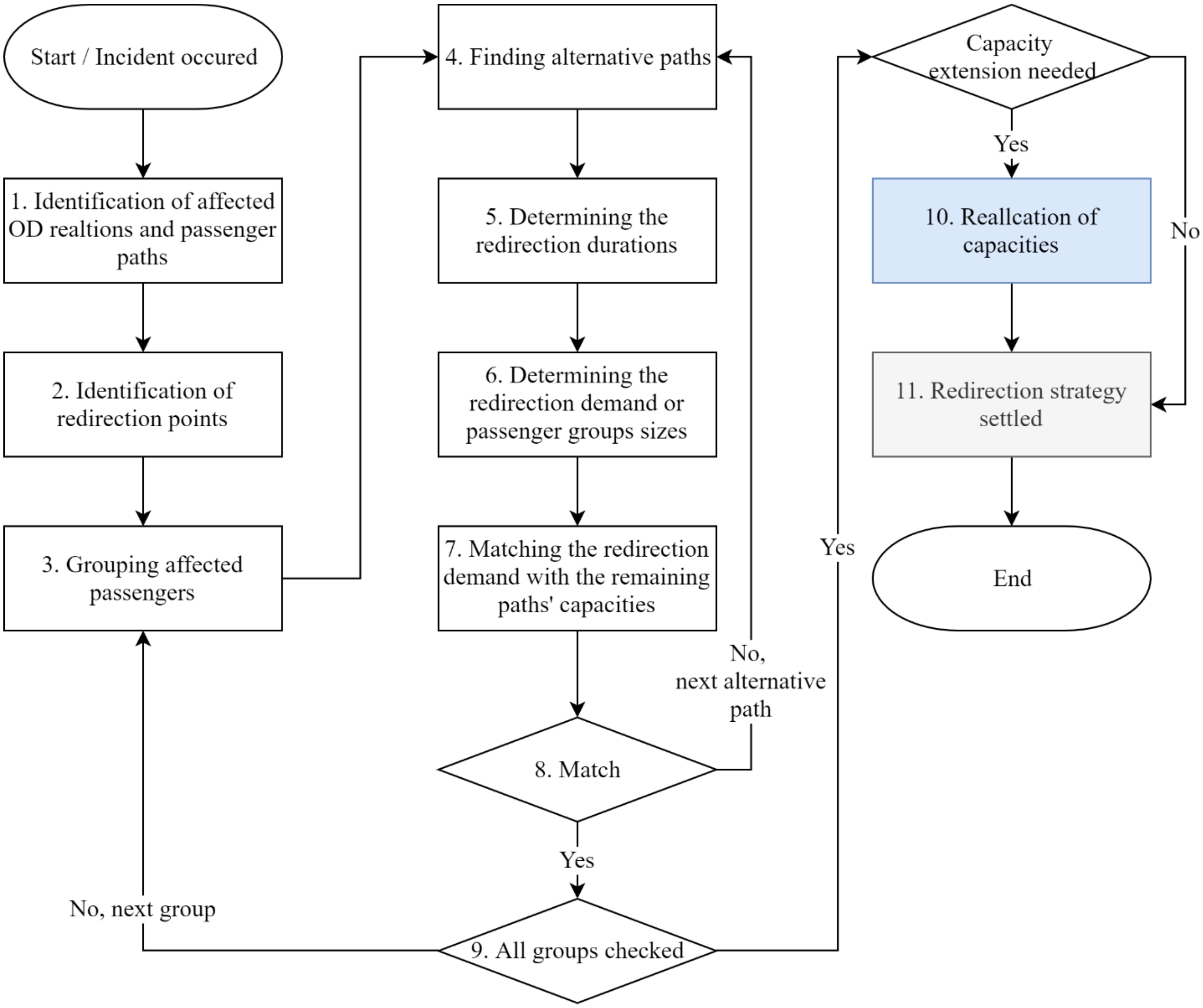

Figure 1 The PCIM algorithm

Based on such data one can expect a certain volume of passengers at a certain time on certain PuT lines *(18)*. It provides information about the existing OD relations and the paths taken by the according passenger flows. Knowing the paths of the respective passenger flows means that one can also determine which of these paths are disrupted by the incident which are therefore the affected ones (**Equation 2**).

$$pf \in PF_{affected} \; if \; p_{pf} \in P_{disrupted} \qquad (2)$$

Where:

$pf = Passenger\ flow \in PF_{all}$
$PF_{all} = List\ of\ all\ passenger\ flows$
$PF_{affected} = List\ of\ affected\ passenger\ flows$
$p_{pf} = Path\ of\ passenger\ flow\ pf$
$P_{disrupted} = List\ of\ disrupted\ paths$

The path of an affected passenger flow reveals the stops those affected passenger flows are passing. If such a stop lies from the perspective of the affected passengers before the incident and has transfer possibilities to unaffected PuT lines, it is in the following referred to as potential redirection point (**Figure 2**). Such stops can be used to redirect affected passengers and instruct them to take an alternative path than the originally planned to their desired destination. Depending on when and where a passenger started his/her trip, the passenger is closer or further away from the incident. The closer to the incident the less potential redirection points lying between a passenger and the incident and therefore the lower the chance to find a reasonable alternative path. It is worth mentioning that transfer stops need to be assessed critically in terms of whether one stop is only served by affected lines or also by unaffected lines. The only exception occurs if the affected lines have different transfer options downstream before reaching the incident. This might make a transfer from an affected line onto another affected line reasonable.

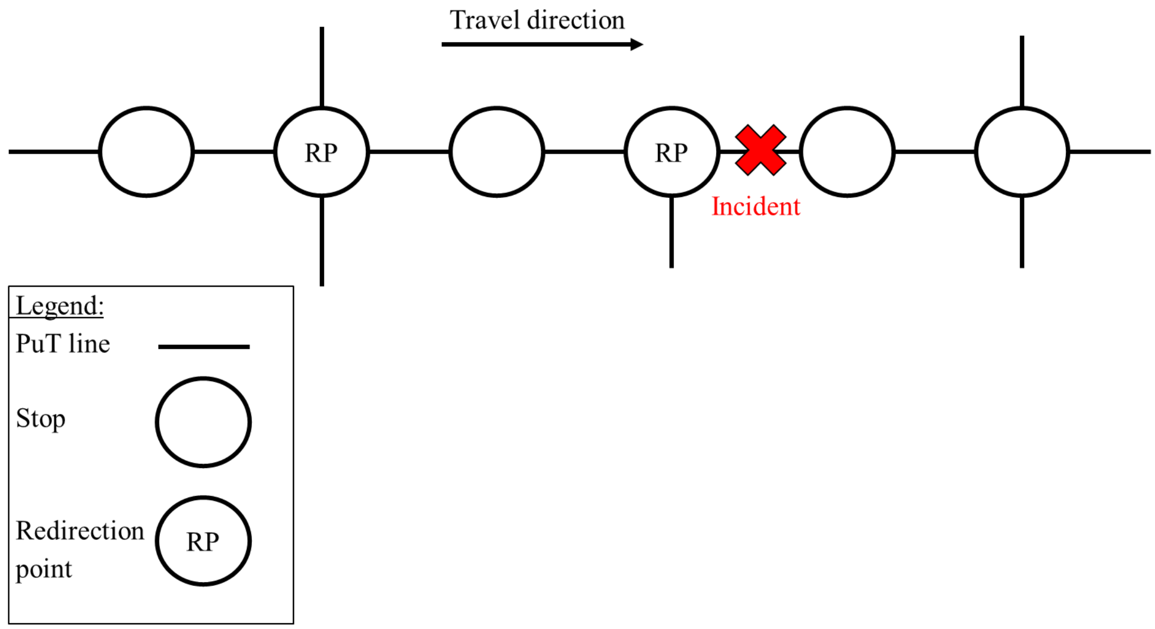

Figure 2 Passengers Passing Points of Redirection

Once it is clear, which redirection points a passenger flow is passing, the flow can be divided into fractions and assigned to specific redirection points depending on which redirection point a certain fraction of a flow is passing next. This process in the algorithm divides these passenger flows into according groups. Additionally, they are divided according to their destination, so fractions of different passenger flows which are assigned to the same redirection point and have the same destination are grouped. The redirection point is then the new origin of a group. Such a passenger group therefore consists of fractions from various passenger flows from several ODs of which the destination is the same but the original origin various (**Equation 3**).

$$g_{RP}^{D} = \sum pf_{PR}^{D} \ with\ pf \ \in PF_{affected} \qquad (3)$$

Where:

$g_{RP}^{D} = Group\ of\ fractions\ of\ passenger\ flows, assigned\ to\ redirection\ point\ RP\ with\ destination\ D$

$pf_{RP}^{D} = Fraction\ of\ passenger\ flow, assigned\ to\ redirection\ point\ RP\ with\ destination\ D$

To consider all possible PuT stops as destinations is in practice too complex and not effective. It would lead to very small groups which is also not desirable. In complex networks it is therefore thinkable to take the last common transfer stop as destination for the grouping process or the first common stop with the originally planned path of a group after the incident site has been passed. Small groups are not desirable because of the channels through which such a redirection information can be passed to passengers, channels such as: Speaker announcements, information displays in vehicles and at stops, the operators' websites, social media, and smartphone PuT applications. If there are many small groups, it would be very difficult to inform all groups about an alternative path separately. The only channel capable of doing so would be the smartphone and only if it would be clear whom to inform about which alternative path. A more realizable approach would be to keep the groups as big as possible and provide the information for the groups on all available channels, which would also increase the number of passengers who receive the information. Investigations of public transport operators in Germany had a similar approach in this matter (*19)*.

The next step is to find alternative paths for the affected passenger groups. There are several shortest-path algorithms in literature. Algorithms such as the k-shortest path algorithm and the A*-algorithm which is an advancement of the Dijkstra algorithm (*20, 21)*. For the here presented purpose a k-shortest path algorithm is suitable to find all alternative paths for each group which fulfill the criteria of being faster than waiting for the dissolution of the incident than staying on the originally planned path (**Equation 4**). Based on the interviews of dispatchers of OCCs it is assumed that the end of the incident is to a certain extend known. However, it was also stated by the interviewees, that incidents sometimes do not develop as expected, the end time of an incident has thereby to be a dynamic variable which is frequently updated to shorten or lengthen the expected duration of the incident. Moreover, the preciseness of this estimation is also highly dependent on the handling dispatchers experience. Based on this expected end time of the incident also the redirection duration is calculated which determines the point of time at which the redirection of passengers onto alternative paths ends (**Equation 5**), which refers to the fifth step in the algorithm.

$$tt_{alt,RP}^{OD} \leq tt_{org,RP}^{OD} + t_{inc} + t_{rec}(t) - t \qquad (4)$$

Where:

$tt_{alt,RP}^{OD} =$ travel time of the alternative path, of a certain OD at a certain redirection point,
$tt_{org,RP}^{OD} =$ travel time of the original path, of a certain OD at a certain redirection point,
$t_{inc} =$ estimated duration of the incident,
$t_{rec}(t) =$ function of the recovery time as a function of time t,
$t =$ time passed since the beginning of the incident.

$$t_{red,RP}^{OD} = tt_{org,RP}^{OD} + t_{inc} + t_{rec}(t) - tt_{alt,RP}^{OD} \qquad (5)$$

Where:

$t_{red,RP}^{OD} =$ redirection duration of an OD at certain redirection point

The recovery time in **Equation 4 and 5** refers to the time between the dissolution of the incident and the return to normal operation. Several factors such as the incident location, its severity and the affected transport mode and availability of replacement vehicles and staff are influencing how quickly a system recovers from an incident. It is therefore difficult to estimate. (*22)* proposes a linear function to represent the recovery time. In the numerical example in the next section a recovery time of 0 minutes is assumed.

Assuming, that passengers are always looking for the fastest path to their respective destinations and that the originally planned and here disrupted path is therefore the fastest, there is a point of time in which it is faster to wait for the dissolution of the incident than taking an alternative path. This point of time is determined by the redirection duration (**Equation 5**), which describes for how long it is reasonable for a certain passenger group to be redirected. It depends on the estimated end time of the incident and the expected travel times of the original and the alternative paths beside the redirection point a group is assigned to. Hence, for each group and each of a group's alternative paths the redirection duration is calculated, since the groups are not assigned to an alternative path yet. At this point, it is not clear whether the respective alternative paths have sufficient remaining capacity or not. This leads to the next and crucial point in the PCIM algorithm, step six (**Figure 1**).

Redirecting passengers onto PuT services without sufficient remaining capacity could lead to overcrowding of those services and thus to secondary incidents which causes additional delays. This is the opposite of the here set objective of minimizing delays. To prevent such secondary incident, the redirection demand needs to be matched with the remaining capacities on the alternative paths, the redirection demand can be assigned onto. The smallest remaining capacity of a section of an alternative path is decisive.

The redirection demand depends on various factors. As previously mentioned, an affected passenger group is defined by the redirection point it is redirected at and the destination it is going to (**Equation 3**). Such a group contains of the fractions of different passenger flows of different ODs which have a common destination and are redirected at a common redirection point. The size or demand respectively of such a fraction of an OD depends on whether a redirection point is the last one of an OD or not (**Equation 6**).

$$q_{red,RP}^{OD} = \begin{cases} tt_{RP}^{OD} * \frac{q_{inc}^{OD}}{t_{inc}} * comp \quad for\ all\ RP \ / \ \{last\ RP\} \\ (q_{inc}^{OD} - \sum_{RP \ / \ \{last\ RP\}} q_{red,RP}^{OD} - q_{wait}^{OD}) * comp \quad for\ last\ RP \end{cases} \tag{6}$$

Where:

$q_{red,RP}^{OD} =$ to be redirected passenger demand of an OD at redirection point RP
$tt_{RP}^{OD} =$ travel time to redirection point from preceding redirection point of an OD
$q_{inc}^{OD} =$ demand of an OD during the duration of the incident
$q_{wait}^{OD} =$ waiting demand of an OD (**Equation 7**)
$comp =$ compliance rate.

In case it is not the last redirection point, the fraction depends on the travel time to the subsequent redirection point. The passenger demand on the network is assumed to be continuously flowing and that one can divide the overall demand of an OD into shares of certain time periods. Hence, the demand of a certain OD's fraction is determined by multiplying the travel time between two redirection points with the demand of the respective OD. (*23)* used a similar approach to develop a quasi-dynamic headway-based transit assignment model. The overall demand was divided into shares of 15 minutes timesteps to bring the headway-based assignment model closer to schedule-based assignment models in terms of precision. In this case, it is used to determine the demand during the incident from the hourly demand according to the incident duration and further divide the incident demand into redirected and waiting fractions.

$$q_{wait}^{OD} = q_{inc}^{OD} * \frac{(t_{inc} - t_{red,\ last\ RP}^{OD})}{t_{inc}} \tag{7}$$

Where:

$q_{wait}^{OD} =$ the waiting passenger flow fraction of an OD

If a redirection point of a group is the last redirection point of a certain passenger flow, its fraction of this group depends on the fractions of this passenger flow which were already redirected on previous redirection points as well as the waiting fraction of this passenger flow (**Equation 7**). The waiting demand of a passenger flow is its fraction which arrives at the last redirection point after the redirection duration elapsed. Therefore, it is more reasonable for this fraction to wait for the dissolution of the incident and take the originally planned path rather than take an alternative path. The according waiting time is the difference of the incident duration and the redirection duration of a particular passenger flow. The remaining redirection demand of an OD at its last redirection point is therefore the rest of its overall demand during the incident after the redirection demands of preceding redirection points and its waiting demand is subtracted from it (**Equation 6**).

The compliance rate in **Equation 6** refers to the ratio of affected passengers who are receiving a redirection information and are following it. After the implementation of such a guidance system for incident situations, a learning curve is to be expected, developing positively with positive passengers' experience of the PCIM. (*3)* tested different values for such a compliance rate, namely, 0%, 100%, a determined value and a logarithm function which takes the derivation of travel times between the fastest and the suggested alternative path into account. In the numerical example in the next section a compliance rate of 100% is assumed.

The longer a passenger flow is redirected the higher is its redirection demand and the higher the demand for desired alternative paths (**Equation 6**). The redirection time again is depending on the difference between the original and the alternative path. The bigger the difference, the shorter the redirection time and therefore the lower the redirection demand. Having alternative paths with a travel time which is almost the original travel time of affected passengers makes it therefore harder to find a suitable alternative path with sufficient remaining capacity.

When redirecting a passenger group onto an alternative path it is important to not exceed its remaining capacity to avoid secondary incidents due to overcrowding. The impact of the passenger redirection onto the PuT system performance and on unaffected paths is meant to be insignificant. From the perspective of the group it is ideal if they can take the fastest alternative. Nevertheless, not fitting on the fastest alternative might mean for another group to be able to be assigned onto this alternative path. The general objective is to reduce the overall gap between planned and actual travel time (**Equation 1**). The worst case would be that not one of the alternative paths have enough remaining capacity. Having a compliance rate of 100% is therefore not necessarily the best scenario. The smaller the groups, the higher the chances of an alternative path's remaining capacity to be sufficient. The best case would be that all groups can be reassigned onto their fastest alternative paths.

The described procedures are repeated for all affected passenger groups at all redirection points until there is a clear strategy for the present incident situation. Meaning, for each to be redirected passenger group an alternative path has been found or it is determined that it must wait for the incident's dissolution.

If this method is implemented in practice, as a next step the information about the redirection strategy is sent out at to passenger information displays at the according redirection points and PuT vehicles as well as to other channels like smartphone applications and social media to instruct affected passengers. Afterwards the incident situation is monitored to consider significant changes in course of the incident's development. If a significant change occurs, it is to be decided if a change of redirection strategy is reasonable or not. The redirection strategy which reassigned all passengers is thereby a new stable status or respectively a new equilibrium during this special incident situation.

Reallocation of Capacity

The second part of the here presented PCIM is about the reallocation of capacities. In case passenger groups could not be redirected on their fastest alternative path in the previous section due to capacity shortages, it is examined in this section whether these capacities can be extended. This is done by reallocating capacities in forms of PuT vehicles onto according desired alternative paths.

In PuT operation, capacities are extended by deploying extra vehicles or rearranging vehicles among the PuT lines. One method in reallocating capacities is the establishment of rail replacement bridging services. Such are established if a section of a rail service cannot be served over a longer period of time and has therefore to be replaced by temporal bus shuttle services covering the disrupted rail section (*24)*. For such bridging services, several busses are deployed from depots or withdrawn from other lines to serve as long as the disruption lasts. Deploying busses from depots or other lines can be very costly in time and caters for shortages on the lines where busses were withdrawn from. This is therefore only done if the incident is to be expected to last longer and has severe impacts.

However, a reallocation of capacities can also be very useful in the combination with the redirection of passengers. In case an affected passenger group cannot be redirected onto their fastest alternative path due to insufficient remaining capacity, it is thinkable to temporally extend the capacity of this path. The more groups fit on their fastest alternative path the bigger is the decrease of the overall delay of these passengers. Moreover, the incident caters for less demand on the affected lines and thereby also for additional vacant capacities. This circumstance is used here to reallocate capacities to further reduce the overall delay of affected passengers.

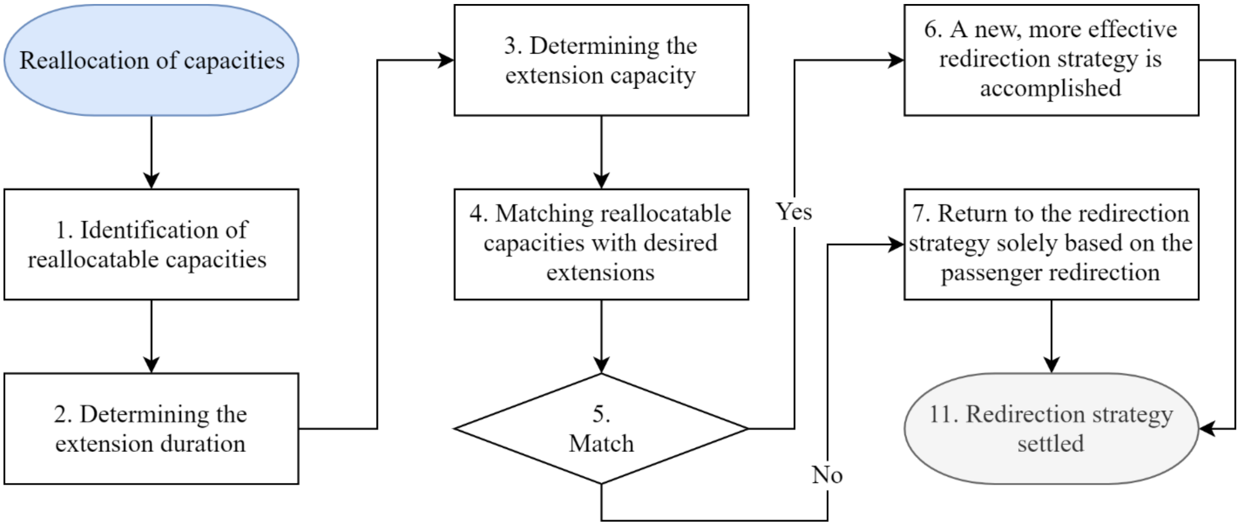

Figure 3 Reallocation of capacities

To do so, the algorithm in **Figure 3** is followed. First, the relocatable capacities need to be identified. Depending on the current passenger demand on the network some lines have capacities to spare. The possibility to reallocate capacities varies between the different PuT modes. In bus operations it is possible to send single vehicles to different lines. When withdrawing busses from certain lines it is crucial that this happen in such a manner that the level of service of such lines is not significantly reduced. Otherwise, if those lines are not capable to cope with their respective passenger demand, secondary incidents would occur, which is to be avoided. In PuT operation this means that a relocatable capacity needs to be at least half of the total capacity of a PuT line for the period of the incident (**Equation 8**).

$$0.5 \geq c_{line} - q_{line} \qquad (8)$$

Where:

$c_{line} = Capacity\ of\ certain\ PuT\ line$
$q_{line} = Demand\ on\ certain\ PuT\ line$

In this case the headway could be doubled, and every second PuT vehicle could be withdrawn to serve on another lane. In the same time, the supporting line maintains a constant headway and certain level of service, the impact on passengers using this line is therefore bearable. Dispatchers speak of a thinning of a line. In this way the level of service drops, however the line is still served properly and can cope with its demand.

It is crucial that this part of the investigation is done without the affected passenger groups because these will be fully or partially assigned to these capacities as a next step. Once it is clear which lines can spare how many vehicles it is to be calculated for how long these vehicles can serve the supported lines. To do so, the travel time from the beginning of their original line to the line which they about to support needs to be considered as well as half of the supported line's headway. This is the average waiting time of supporting vehicles to fit in the service frequency of the supported line. These factors determine the starting time of the capacity extension (**Equation 9**). It is assumed that the vehicles are available when the incident is noticed.

$$t\_start_{extansion}^{line} = t_{start}^{incident} + \frac{h_{supported\ line}}{2} + tt_{line} \qquad (9)$$

Where:

$t\_start_{extansion}^{line}$ = Starting time of the extansion of a certain line
t_{start}^{inc} = starting time of the incident
tt_{line} = travel time of buses from their origin line to the supported line
$h_{supported\ line}$ = headway of the supported line

$$t\_end_{extansion}^{line} = t_{end}^{incident} - \frac{h_{supporting\ line}}{2} - tt_{line} \qquad (10)$$

Where:

$t\_end_{extansion}^{line}$ = end time of the extension of a certain line
$t_{end}^{incident}$ = end time of the incident
tt_{line} = travel time of buses from their origin line to the supported line
$h_{supporting\ line}$ = headway of the supporting line

To calculate the end time of the line extension, one needs to know the time at which the demand on the supporting line exceeds half of its capacity again. This can be for example the end of the incident, when the demand returns to its original paths. The decisive factors are the travel time between the supporting and supported line as well as half of the headway of the supporting line, which is the average waiting time of returning vehicles to fit back in the service frequency of their original line (**Equation 10**). The travel time between the lines depends on the number of runs a vehicle of the supporting line does before returning to its original line. This is because the supporting vehicles need either to travel to and from the beginning of the supported line or to the beginning and from the end of the supported line, depending if the number of runs is odd or even. The number of runs depends on the run time of the supported line as well as the duration of the extension. It is assumed that the number of runs is one and the travel time for the supporting vehicles is calculated accordingly. This needs to be verified and readjusted if necessary. The duration of the extension is simply the rest of the end time and start time of the extension. **Equation 9 and 10** can therefore be summarized in **Equation 11**.

Here it is assumed that the vehicles always serve the full stretch of a line and not only a part of it. The size of the extension capacity is calculated by dividing the extension duration through double the headway of the supporting line and multiply it with the capacity of one vehicle (**Equation 12**). This is done for all potential alternative paths which were found in the first part of the here presented method about the redirection of passengers. Now, for every alternative path the potential capacity extension is known.

$$t_{extension}^{line} = t_{incident} - \frac{h_{supported\ line}}{2} - \frac{h_{supporting\ line}}{2} - tt_{start}^{line} - tt_{end}^{line} \qquad (11)$$

Where:

$t_{extansion}^{line}$ = extansion duration of a certain supported line
$t_{incident}$ = incident duration
tt_{start}^{line} = travel time to the start of the suppprted line
tt_{end}^{line} = travel time from the end of the supported line (in case of an odd number of runs)

$$cap_{extansion}^{line} = \frac{t_{extansion}^{line}}{2 * h_{supporting\ line}} * cap_{vehicle} \qquad (12)$$

Where:
$cap_{extansion}^{line}$ = extansion capacity
$cap_{vehicle}$ = capacity of the vehicle

As a next step, the possible capacity extensions are matched with the needed capacity extensions for the redirection of passenger groups. Starting with the biggest group which could not be assigned to its fastest alternative path and for which it is hardest to find an alternative path. The process is stopped when all groups have been checked or all possible extensions are used. If one or several groups are reassigned to faster alternative paths due to the reallocation of capacities, a new and more effective redirection strategy is accomplished. With the end of the redirection of passengers does also the reallocation of capacities end.

RESULTS

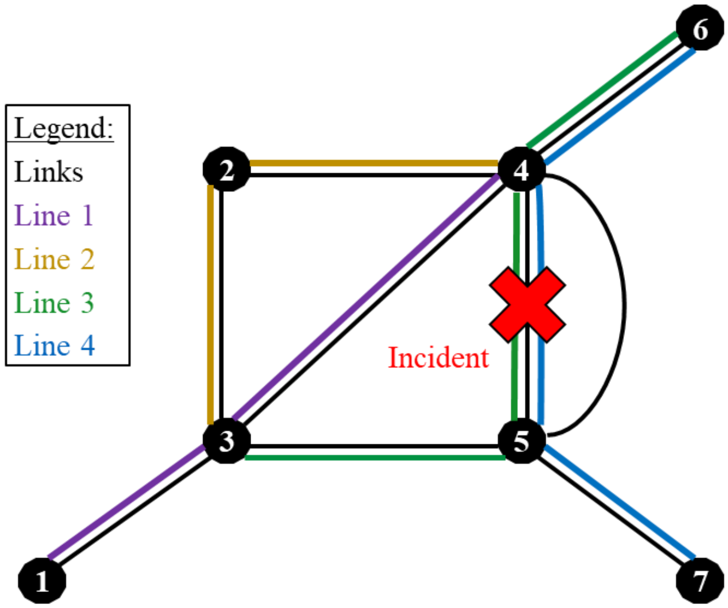

Figure 4 Simple artificial network

A simple artificial network, inspired by (21) (**Figure 4**), is used here to demonstrate the effects of the PCIM method. Even though this network only contains seven nodes and four PuT lines, its level of complexity is sufficiently high for a redirection of passengers to be possible. Logically, the redirection of passengers is only possible if alternative paths are existing.

In the first example all PuT lines are bus lines. Three scenarios are tested: In the first scenario the passengers are not informed in any kind and just take their paths as planned. There is no redirection of passengers and no reallocation of capacities. The busses are rerouted on the adjacent arc to avoid the incident, which is a usual supply centric reaction to incidents in bus operations. In the second scenario, in addition to the aforementioned dispositive measure, the passengers are redirected onto certain alternative paths. In the third scenario, capacities are additionally reallocated in a way that more affected passengers can be redirected onto faster alternative paths without exceeding their capacities. The results of these three scenarios of this numerical example is depicted below (**Figures 5**).

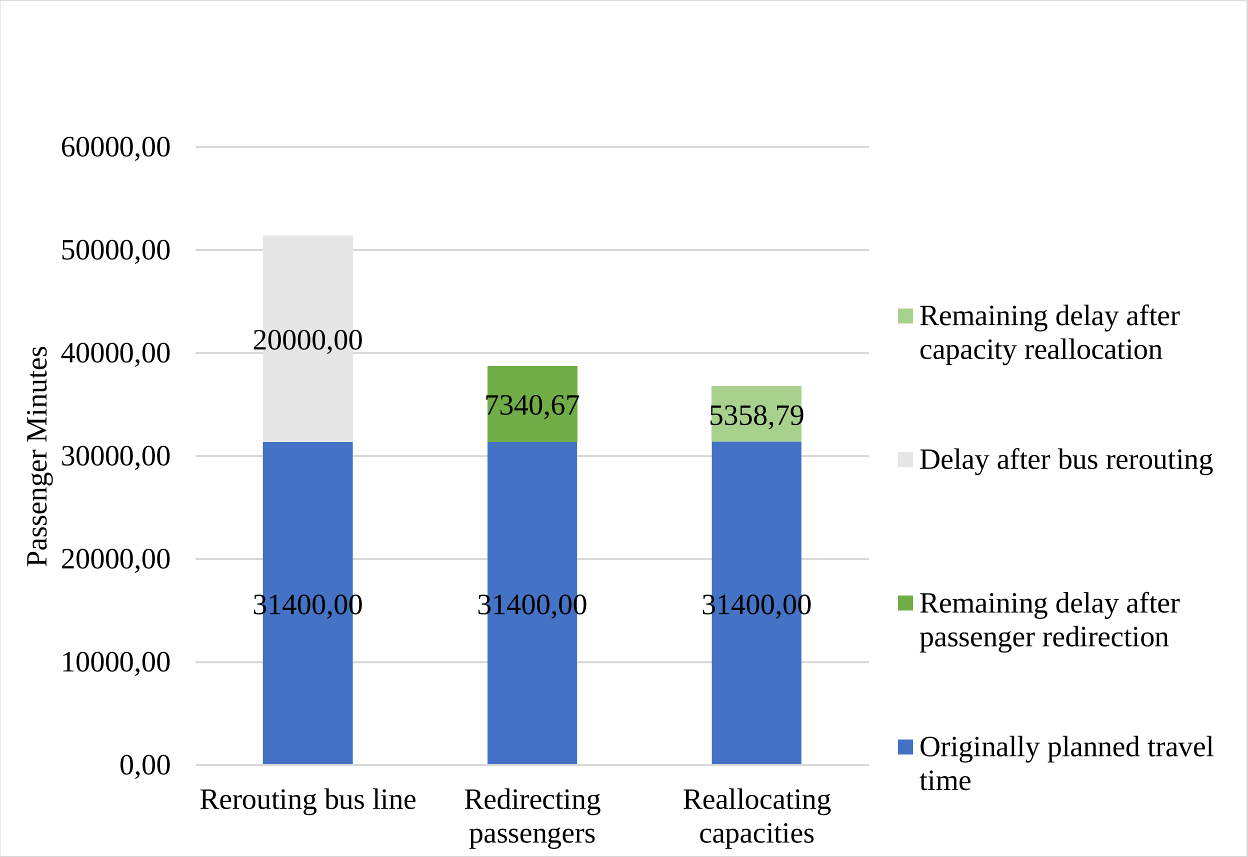

Figure 5 Bus lines: overall passenger travel time of all affected passengers in passenger minutes

The results clearly show that in the first scenario, the affected passengers have by far the biggest delay. The overall originally planned travel time, shown in blue is 31,400 passenger minutes. In case the affected passenger stick with their originally planned paths the bus line has an additional travel time of 10 minutes due to the rerouting around the incident. With 2,000 affected passengers does this add up to a delay of 20,000 passenger minutes.

In the second scenario the affected passengers for which it is timewise reasonable to change their path are redirected onto alternative paths which can bear the additional demand. This already leads to a tremendous reduction of the overall delay by 12,659.33 passenger minutes to an overall delay of 7,350.76 passenger minutes.

However, in the second scenario, not every affected passenger group could be redirected on its fastest alternative path due to insufficient remaining capacity on these. Therefore, the reallocation of capacities has an additional positive impact on the overall travel time of affected passengers. By extending the capacities of the fastest alternative paths of affected passenger groups, all groups could be redirected onto their ideal alternative paths. This reduced the overall delay by another 1,981.88 passenger minutes for all affected passengers.

The results clarify that the redirection of passengers during incidents with respect to the PuT lines' capacities cater for a tremendous drop in the overall delay of affected passengers. This effect is even improved by the reallocation of indispensable capacities towards the identified fastest alternative paths of the affected passengers. Nevertheless, this comes also along with a reduced service quality of passengers, affected as well as not affected, who are riding the supporting line because this line is thinned out. In the here presented numerical example it is the second line (yellow) supporting the first line (violet).

This negative side effect of the reallocation of capacities vanishes in a futuristic PuT mode such as the DART. As explained above the DART is an autonomous and modular PuT mode. Three coupled DART modules have the same capacity as one city bus. One run is therefore not served by one bus but by a platoon of three modules. This makes the DART more suitable for capacity reallocation than today's busses. Since this effect can only be seen in the third scenario in which capacities are reallocated, the first two scenarios show the same results as in the example above in which all lines are bus lines (**Figure 6**).

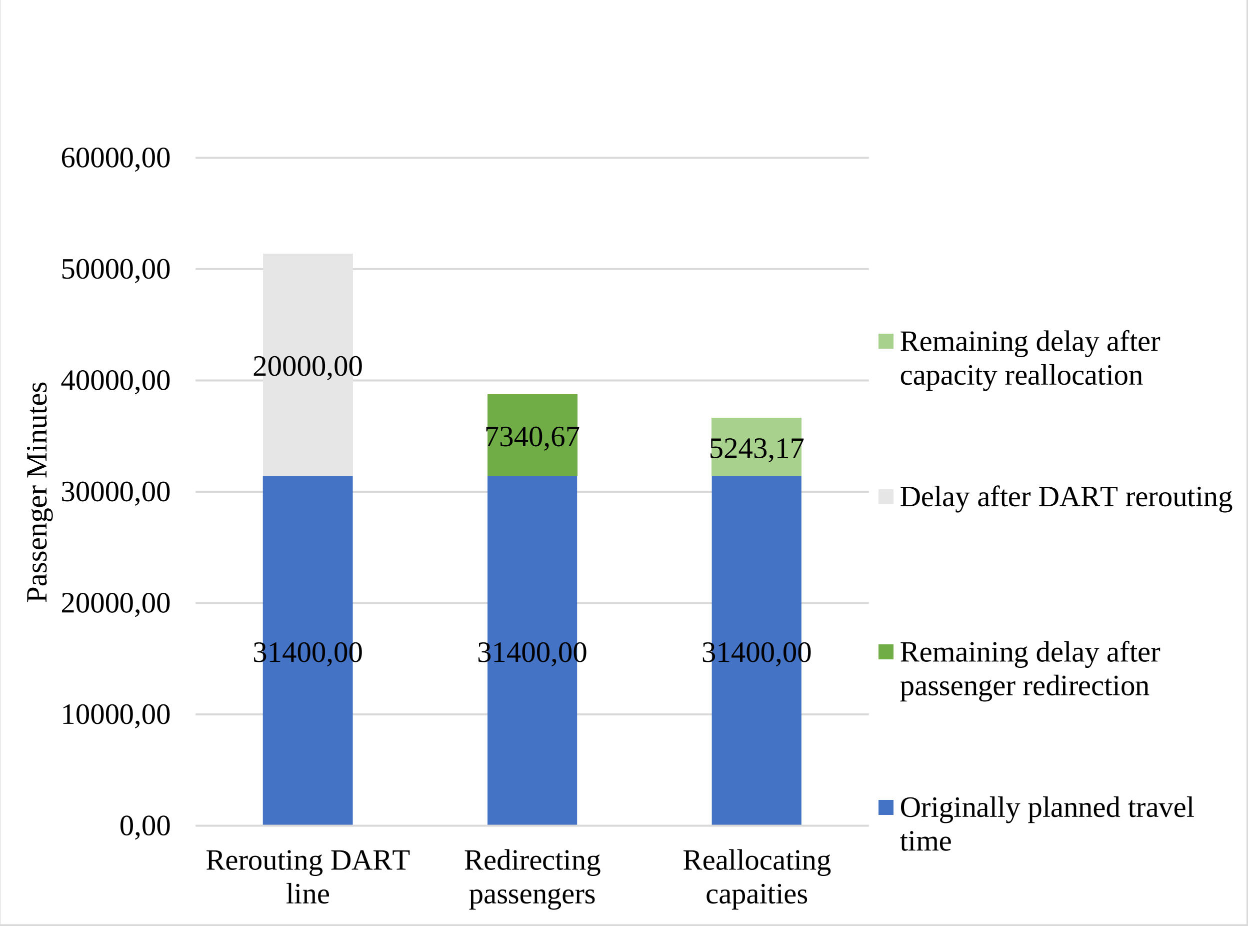

Figure 6 DART lines: overall passenger travel time of all affected passengers in passenger minutes

However, in the third scenario the DART shows a slightly better result compared to the bus. While after the reallocation of busses there is still an overall delay of 5,358.79 passenger minutes, there is only an overall delay of 5,243.17 passenger minutes after the reallocation of DARTs. This is due to the modular setup of the DART which allows for capacity splitting; implies, each run can still be served on the supporting line just by less modules per run, while the rest of the modules are sent to extend the capacities on the fastest alternative paths for the affected passenger groups.

CONCLUSION AND FUTURE WORK

A novel method for passenger centric incident management in public transport has been introduced here, focusing on incidents of any kind in urban public transport networks. Up until now publications in passenger centric incident management focused on major disruptions in rail networks.

First numerical results are shown which reveal that this method has the potential to significantly reduce the overall delay of passengers affected by an incident in a PuT network. This reduction is achieved by redirecting affected passengers onto alternative paths in consideration of the paths' remaining capacities. The effect is additionally improved, by additionally reallocating indispensable capacities, the delay could be reduced even further.

The first steps in the development of a PCIM approach are done which is suitable for any kind of PuT network and any kind of incident. Future work will focus on the implementation of the here presented algorithm into a sophisticated simulation environment. Especially regarding the capacities' reallocation, the use of a more complex PuT network can prove in which scenarios such a reallocation is feasible. In such a network the DART probably can fully unfold its potential.

Additionally, the PCIM method has a high potential for optimization. First, redirecting certain passenger groups onto available alternative paths is an optimizable problem. Second, reallocating certain dispensable capacities onto desired alternative paths is an optimizable problem as well. Moreover, these two problems are interdependent. To tackle these optimization challenges, a generic algorithm will be installed to find the optimal redistribution of passenger groups and the according optimal redistribution of capacities in a PuT network.

With an optimal redirection of affected passengers and the optimal reallocation of dispensable capacities, incident management in PuT will meet a new level of reliability. This increases PuT's attractiveness which motivates more people to switch to public transport.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Frederik R. Bachmann, Andreas Rau, Fritz Busch; data collection: Frederik R. Bachmann; analysis and interpretation of results: Frederik R. Bachmann; draft manuscript preparation: Frederik R. Bachmann. All authors reviewed the results and approved the final version of the manuscript.

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