Resilience of Railway Stations: Impacts of Strategic Infrastructure Modifications

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1 INTRODUCTION

The increased demand for passenger and cargo transport, combined with slow growth in rail infrastructure, inadvertently led to congestion on rail networks. Consequently, rail networks have become more vulnerable to unforeseen incidents. In such conditions, dispatchers modify plan using quantitative understanding of the disruption and/or inherent flexibility in the original plan. Further, a resilient rail network enables swift recovery and ensures minimal impact of disruption. Several studies have focused on assessing the rail networks resilience or identifying the crucial elements during disruptions (Chen & Miller-Hooks, 2012, Khaled *et al.*, 2015). The predominant method to assess the criticality of network elements having one or more elements failures involves interdiction approach (Gedik *et al.*, 2014, Bababeik *et al.*, 2017, Kuttler *et al.*, 2024). In addition, network design problems are employed to simulate network modifications (Lou & Zhang, 2011, Khaled *et al.*, 2015, Azad *et al.*, 2016). To measure vulnerability, Khaled *et al.* (2015) exploit the notion of increased cost per disrupted element. Azad *et al.* (2016) demonstrate that gradual rise in pre-disruption costs enhances network resilience, allowing for a balanced approach. Vulnerability refers to a system's susceptibility to disruptions that have the potential to impact its operations whereas, resilience is the capacity of a system to rapidly recover from adversities.

Other metrics employed to quantify resilience include time and resources required to return the network to its typical state (Chen & Miller-Hooks, 2012, Fiondella *et al.*, 2015). Szymula & Bešinović (2020) introduce passengers' perspective in assessing the vulnerability of rail systems. For a comprehensive understanding of resilience in transport, readers are encouraged to refer (Zhou *et al.*, 2019, Bešinović, 2020). Existing literature indicates that only a few studies investigate on the effects of infrastructural changes on system resilience. In addition, infrastructure managers encounter challenges when analyzing infrastructure modifications aimed at maximizing efficiency within a limited budget. This motivates the present study, which focuses primarily on examining the impact of minor infrastructural modifications near station area on system resilience. It may help infrastructure managers identify critical resources, assess disruption severity, and make strategic decisions to improve system resilience.

2 METHODOLOGY

Problem description. The present research analyses the impact of new infrastructure layout on system resilience. It considers two types of infrastructural modification in the vicinity of

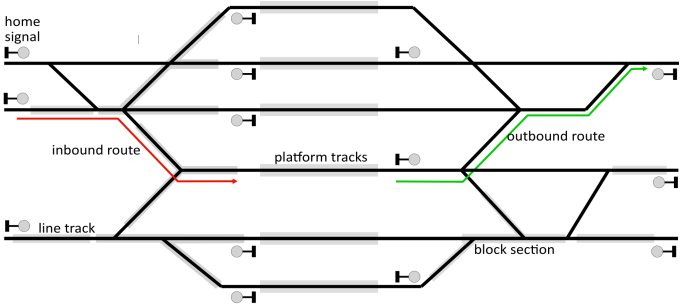

Figure 1 – *A schematic of station area and elements used in developing a mesoscopic model*

Table 1 – *Description of sets, parameters and decision variables used in the MILP model*

Not.	Description
T	set of all trains, indexed by t, t'
P	set of all platforms at the station, indexed by p
R_t^+ / R_t^-	set of feasible incoming/outgoing routes for train t
R_{pq}^+ / R_{pq}^-	set of incoming/outgoing routes to platform track p in the direction q
μ_t^r / ν_t^r	is 1 if train t is originally assigned with inbound/outbound route r; 0 otherwise
$p(r)$	platform track number on route r
α_t^r / β_t^r	$=1$ if train t takes route r as the incoming/outgoing route; 0 otherwise
$y_{tt'} / z_{tt'}$	$=1$ if train t departs before train t' from the home signal/platform; 0 otherwise
σ_t^+ / σ_t^-	$=1$ if there is a deviation in inbound/outbound route for train t; 0 otherwise
Δ_t	deviations from original platform track assignment

station: addition of new crossing track - connecting more tracks, and installation of new signals in the station - allowing for bi-directional train movements. The station area encompasses various components of the infrastructure, such as signals, track sections, switches, and platform tracks. Multiple track sections are grouped together to form block sections, smallest units controlled by the signalling system. It ensures that only one train occupies a specific block at any given time. The sequence of block sections traversed by a train determines its route. Further, sequence of adjacent block sections partition the station area into three distinct route sections: in-route section, platform, and out-route section. The route sections help identify potential conflicts based on shared elements. Sections with shared elements are referred to as multi-block sections. The study utilises a mesoscopic methodology to analyse infrastructure systems; thus, considers multi-block sections as a whole, see Figure 1.

The study employs a train platforming model to modify assigned train routing and platforming decisions across various disruption scenarios, aiming to quantify system's resilience. We examine two most common variants of disruption: switch failure and platform closure. Additionally, to conduct a thorough analysis, we investigate the effects of diverse disruptions occurring at peak and off-peak hours, varying in duration. The key performance indicators utilized to assess both infrastructures include metrics such as total delays, recovery times, platform changes, and performance drop, i.e. the maximum decrease in the number of trains that passes through the station within a given time period.

Mathematical Model. We propose a new optimisation model that utilizes the concept of train platforming problem (TPP) to revise the given schedule, consisting of arrival/departure times (a_t, d_t), dwell times (δ_t), running times (τ_t), assigned platform (p_t), operating direction (q_t), and routes for each train. The decision variables include adjusted arrival/departure times $(\hat{\boldsymbol{a}},\hat{\boldsymbol{d}})$, dwell times $(\hat{\boldsymbol{\delta}})$ and waiting times $(\hat{\boldsymbol{w}})$ for trains, as well as alternative routing (σ_t^+/σ_t^-), platforming (Δ_t) and reordering $(y_{tt'}/z_{tt'})$. Other notations and decision variables used in the model are outlined in Table 1.

The formulation of the TPP for adjusting platforms and routing is as follows:

$$\begin{aligned}
\text{Min. } & \omega_d \sum_{t\in T}(\hat{a}_t - a_t) + \omega_p \sum_{t\in T} \Delta_t + \omega_r \sum_{t\in T}(\sigma_t^+ + \sigma_t^-) && && (1)\\
s.t. \quad & \sum_{r\in R^+_{pqt}\cap R^+_t} \alpha^r_t - \sum_{r\in R^-_{pqt}\cap R^-_t} \beta^r_t = 0 && \forall t \in T, p \in P_t && (2)\\
& \sum_{r\in R^+_t} \alpha^r_t = 1 && \forall t \in T && (3)\\
& f(\boldsymbol{\hat{a}}, \boldsymbol{\hat{d}}, \boldsymbol{\hat{w}}; \boldsymbol{\tau_t}, \boldsymbol{ah}) + M\phi(\boldsymbol{y}, \boldsymbol{\alpha}) \geq 0 && \forall t, t' \in T, t \neq t' && (4)\\
& g(\boldsymbol{\hat{a}}, \boldsymbol{\hat{d}}, \boldsymbol{\hat{\delta}}; \boldsymbol{\tau_t}, \boldsymbol{ah}) + M\psi(\boldsymbol{z}, \boldsymbol{\alpha}, \boldsymbol{\beta}) \geq 0 && \forall t, t' \in T, t \neq t' && (5)\\
& \alpha^r_t |(p(r) - p_t)| \leq \Delta_t && \forall t \in T, r \in R^+_t && (6)\\
& \Delta_t \leq |P| - 1 && \forall t \in T && (7)\\
& \sigma^+_t \geq |\alpha^r_t - \mu^r_t| && \forall t \in T, r \in R^+_t && (8)\\
& \hat{a}_t, \hat{d}_t, \hat{w}_t, \hat{\delta}_t, \Delta_t \in Z^+_0 && \forall t \in T && (9)
\end{aligned}$$

The objective function (1) aims to minimize the delay in train arrivals, deviations from original platform track and route assigned. The route changes determine whether a train follows different line tracks for its inbound or outbound routes. The value for ω represents the penalty associated with each term in the objective. Constraints (2) and (3) are referred to as station flow conservation constraints. Constraints (4) and (5) ensure the arrival, departure, waiting and dwell times for trains. In constraints (4), functions f and ϕ ensure that the arrival and waiting times for trains are determined by running times, assigned routes, and conflicts related to resources on their respective routes. Similarly, in constraints (5) functions g and ψ ensure arrival and dwell times for trains. Constraints (6) and (7) limit the deviation in platform changes for trains. The variation in incoming train routes is estimated by constraints (8). Similarly, we impose constraints to estimate the deviation of outbound train routes. The modulus in constraints (6) and (8) can be easily transformed into linear form. Finally, constraints (9) define the variables domain.

3 RESULTS

This section provides a comprehensive analysis of results obtained by performing computational experiments on real-life medium size station in Germany. During pre-processing phase, we ascertain feasible routes for each train, as well as multiple-block sections that constitute these routes. We analyse train schedule for a specific day of the year and randomly generate disruptions of different types and duration.

The resilience of both infrastructure settings is evaluated in terms of overall objective, delay, recovery time, and performance drop. Figure 2 exhibits the impact of switch failure on different metrics. It is evident that the impact of a short disruption, for instance 15 or 30 minutes, on the newer layout is relatively similar. Nevertheless, as the duration of disruption increased, we observed a remarkable improvement in all metrics, resulting in an impact that is 1.5 times lower than that of the previous layout. We exhibit similar results on all different metrics during platform closures.

4 CONCLUSIONS

This study aims to examine the importance of minor/local changes to infrastructure on the resilience of rail operations in the event of disruptions. Our goal is to provide infrastructure

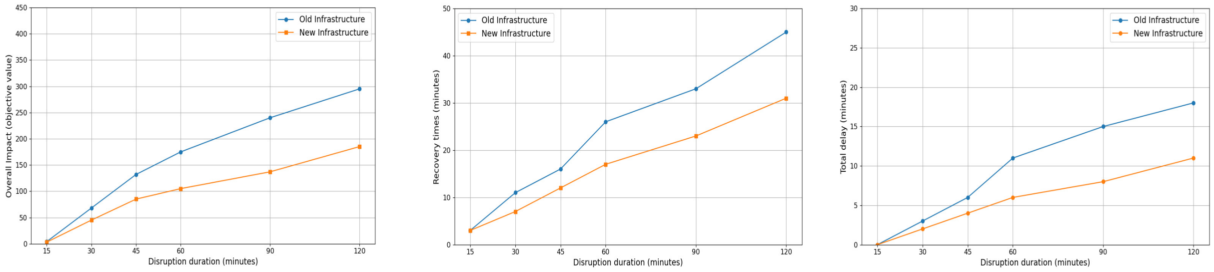

Figure 2 – *Comparison on different metric for both infrastructures*

managers with the ability to measure the effect of changes and assist in making strategic decisions. The proposed method offers an intelligent approach to identify crucial modifications in the vicinity of a station area, that eventually improve operational efficiency during real-time operations. Future research should focus on investigating two critical aspects. Firstly, we can examine the economic advantages of carrying out changes to the infrastructure as in the cost per minute of delay. The economic benefit also facilitates an efficient trade-off between costs incurred prior to and after the disruption. Furthermore, the study can be extended by incorporating a capacity benefit analysis. Additional capacity for the new infrastructure can be identified to add new trains based on the projected future demand.

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