Advances in Reliability, Safety and Security, Part 8 – Kołowrocki, Magryta-Mut (eds.)
© 2024 Polish Safety and Reliability Association, Gdynia, ISBN 978-83-68136-20-3 (printed), ISBN 978-83-68136-07-4 (electronic)

Advances in Reliability, Safety and Security

ESREL 2024
Monograph Book Series

Analysing Railway Network Interdependencies: Simulation of Reactionary Delay and Automated Rescheduling

Kang Rui Tan[a], Rasa Remenyte-Prescott[a], Darren Prescott[a], Julia Culley[b]

[a]*Resilience Engineering Research Group, University of Nottingham, United Kingdom*
[b]*Network Rail, The Quadrant: MK, Elder Gate, Milton Keynes, MK9 1EN, United Kingdom*

Abstract

This research is conducted to study the interdependencies within a multi-line railway network during disruption events. Disruptions will not only cause primary delay, which is directly linked to the disruption, but also trigger reactionary delays. The reactionary delay propagates throughout the network, posing a great challenge for the network operators in deciding on an effective contingency plan. A generalised discrete event simulation (DES) model is developed in this paper as a novel method to investigate the railway network interdependencies on multiple lines and mimic the propagation of the reactionary delay across the railway network effectively and concisely. The simulations conducted involve a scenario where contingency plans are implemented and a scenario where no action is taken. To ensure the practicality of this model, real-world information including timetable, infrastructure layout, and industry best practice are considered in this model. The key findings demonstrate that the primary delay will stop increasing when the disruption ends whereas the propagation of reactionary delays will not cease if no measure is taken. Cancelling trains strategically can effectively halt the propagation of reactionary delay. This simulation model serves as a useful advisory tool for network operators, enabling them to proactively manage disruptions by predicting the outcomes of contingency plan implementations before execution, thereby effectively mitigating the propagation of reactionary delays within a regional railway network.

Keywords: *railway network interdependencies, reactionary delay, discrete event simulation, automated rescheduling*

1. Introduction

Disruptive events on railways can happen anytime, interrupting the railway network operation. In the first quarter of 2023 (April to June), out of the 1.8 million scheduled trains, only 70.7% of the trains arrived on time (Office of Rail and Road, 2023a). Furthermore, 69531 train services were partially or fully cancelled (Office of Rail and Road, 2023b). The impact of delayed train services is detrimental to delivering safe, reliable, and efficient services to customers, particularly in promoting railway usage to the public and enterprises.

(Vansteenwegen et al., 2013) mentioned that adequate headway should be scheduled between two trains on the same line to prevent delays to the subsequent trains in the event of a delay affecting the first train. However, certain network sections run at full capacity during peak hours, so the gap in the timetable between trains is very close. If the disruption happens during peak hours or the disruption period is long, it will not just cause delays in the train services operating during the disruption duration but also result in knock-on delays that can sustain for the next few hours. A knock-on delay happens if a train is disrupted on the railway line, preventing the trains travelling on the same line from passing through it (Carey & Kwiecisiski', 1994). The impact of the blockage is severe, even if only one small section of the line is closed. It will affect not just the nearby trains but also the trains across the network due to the knock-on effect. (Higgins & Kozan, 1998) suggested that the main reason for knock-on delays is route conflicts and lengthened boarding and alighting time of passengers.

According to the railway infrastructure owner and operator of Great Britain, Network Rail, delays are categorised into two groups, primary delay, and reactionary delay, also known as knock-on delay. Primary delay is the exogenous delay which can be caused by any disruption. The reactionary delay is the knock-on delay, which develops from the primary delay, depending on the capacity utilisation and the duration and frequency of the primary delay. For instance, closing a line in Cheltenham will slowly impact the whole railway network and spread congestion across the country for 20 hours (*Knock-on Delays - Network Rail*, n.d.). During periods of disruption, train services must slow down to accommodate the process of service recovery. The crew arrangement will also be directly affected, as the train crews may not be able to reach their designated locations punctually for subsequent tasks, resulting in an escalation of knock-on delays. The delayed arrival of trains causes a shortfall of preparation time for the subsequent trip, further prolonging the delay time of the upcoming train services.

(Rinaldi et al., 2001) concluded in their research that determining, comprehending, and investigating the interdependencies among the infrastructures have become increasingly significant due to the greater interconnectedness and complexity of infrastructures, often with high levels of centralization of control. However, analyzing these interdependencies proves to be challenging and complex. In this research, the interdependencies within the railway network are examined from the standpoint of how disruptions propagate throughout the network and impact the overall performance of the regional railway network.

During a disruption, individual trains may be cancelled or delayed strategically to minimise the wider impact on the railway network, prioritising the overall railway network efficiency. Pre-written contingency plans are introduced to guide the operators in managing the disruptions to mitigate the effects of the disruption. However, the current industry practice mainly depends on the operators' judgement with the effectiveness of the decisions becoming evident only after implementation. Furthermore, the possible contingency plans cannot be explored automatically, leading to slow reaction times and further delays.

While it is challenging to further reduce the impact of the primary delay due to the time needed to address disruptions, measures can be taken to minimise the propagation of reactionary delays. Simulating disruption events and analysing the contingency plan outcomes before implementation could greatly help in choosing the most effective contingency plan.

Even though numerous works in optimising the rescheduling approaches have been conducted, there remains a scarcity of studies in the literature on the knock-on delay in railway networks, which may cause the ineffectiveness of the optimisation method in real-world scenarios. (Hwang & Liu, 2010) introduced a simulation model to estimate the knock-on delay of the Taiwan Regional Railway. However, the authors mentioned that the model is only applicable to one railway line due to the complexities inherent in railway networks. (Ilalokhoin et al., 2023) developed a methodology and model to assess the systematic performance and resilience of rail networks, capturing the intricate interdependencies among the infrastructure systems. While this model adeptly simulated the impact of component failures on the network, it falls short in swiftly simulating conditions during disruptions. The limitation impedes the model's ability to assist the network operator in making prompt decisions in a disruptive event.

In this paper, a generalized Discrete Event Simulation (DES) model is developed as a novel method to investigate the railway network interdependencies on multiple lines and mimic the propagation of reactionary delay across the railway network. DES is one of the most popular simulation techniques for simulating dynamic systems (Tendeloo et al., 2019). Reviewing the result of the research conducted by (Zou & Liu, 2021),showed that the simulation of the movements of rolling stocks on the single-line railway could be conducted rapidly due to the high efficiency of the DES method. This model will include multiple railway lines, to analyse the propagation of reactionary delays in the railway network triggered by a primary delay due to a disruption occurring at a specific point in the network. The model is subsequently applied for automated timetabling, according to the result derived from the simulation.

The remainder of the paper is organised as follows: Section 2 explains the research methodology. Section 3 describes the DES model. Section 4 presents some results and discussion derived from the model. Section 5 summarises the results and suggests possible future works.

2. Research Methodology

The disruption management considered in this paper is in accordance with the guidelines provided by Network Rail (*Knock-on Delays - Network Rail*, n.d.; RSSB, 2021; RSSB et al., 2021; Steer Group et al., 2020). A thorough discussion is conducted with one of the co-authors of this paper, who is the Performance Analysis Manager of Network Rail, to gain a comprehensive understanding of the practical implementation of disruption management in real-life scenarios.

2.1. Model Framework

The layout of railway infrastructure varies across the railway network, which is a big challenge to modelling a regional railway network that consists of numerous routes. To develop a generic model which is applicable to all routes, it is crucial to incorporate only consistent information across the railway network and key details of the railway infrastructure layout. This approach ensures an efficient simulation model that strikes a balance, being neither excessively complex nor time-consuming, while still maintaining the accuracy of the simulation result. To ensure the model's practicality in studying the propagation across a regional railway network, actual timetables of distinct railway lines in the regional railway network are applied. The timetables for each line consist of two schedules, one for the up-direction and another one for the down-direction, which are designed for a single day and repeated daily. The information obtained from the timetables includes the headcode (Train ID) and departure and arrival times of the trains at each station.

Railway network disruptions can happen for many reasons. These disruption events are grouped into two categories: full and partial line blockage, due to the certainty that these disruptions will result in obstructions on the line. The classification streamlines the complexity of the model to consider various disruption causes, making the model more adaptable to a wide range of disruptions. In the event of a partial-line blockage on a multi-track railway, the trains can be rerouted to another track if one track is obstructed, allowing them to bypass and continue with the journey During a full line blockage, the flexibility of switching tracks is limited since all tracks are disrupted. As a result, train services will experience delays until the end of the disruption. To incorporate this mechanism into the model, the location of switches and the number of tracks are key pieces of information for accurately simulating the track switching. They act as constraints in the model, affecting how the switching of trains can be operated during a partial blockage.

To initiate the simulation, the details of the disruption, including the location of disruption, disruption starting time and disruption duration will be inputted. In the UK, the location of disruption is usually represented by STANOX, which are the codes utilised to describe the station and non-station locations such as sidings and junctions (RSSB, 2021). The direction of the track (up or down) which is disrupted shall be provided too. The disruption starting time refers to the time when the disruption is reported, and the disruption duration is the estimated time taken to resolve the disruption. In current practice, the disruption duration is commonly suggested by the engineers who are sent to the site to examine the situation.

In the UK, the prevalent approach of scheduling train services is to coordinate a connecting train after the arrival of a train at its destination. This arrangement enables the train's return journey to its origin, to ensure that the rolling stock and the train crew are transported back to their starting location at the end of the day. If a train is delayed, it will cause further delays to its connecting train. Therefore, it is essential to consider the connectivity between trains so that the propagation of reactionary delay can be simulated appropriately.

2.2. Mitigation Plan

During the disruption, the primary delay occurs when a train is obstructed and unable to continue its journey. The primary delay leads to reactionary delays instantly, as the blocked train not only obstructs the train behind it but also affects the schedule of the subsequent train. T1154 toolkits and Integrated Train Service Recovery Program (ITSR) were introduced by (RSSB, 2021) to aid the network operators in enhancing the response time, management, and recovery from disruptions. The service alteration suggested by the toolkits includes full or partial cancellation, special stop or run fast order, and diversion from the normal route. In real-world cases, commonly implemented contingency plans involve reducing the dwelling time of the train at each station and the preparation time for the subsequent train.

Several mitigation plans can be employed during a disruption event. This is done to minimise the delay minutes as much as possible to prevent propagation throughout the network. In this paper, the simulation model will keep running until the propagation of delays halts and the network is fully recovered to its normal state. In addition, in cases of partial blockage, the simulation model allows trains to switch to another lane to bypass the blockage, if the circumstances permit. Finally, two scenarios will be simulated: the first one with no recovery action, and the second with the reduction of preparation time and the cancellation of train services. The result will be analysed to determine the total delay minutes of each disrupted train service. The spread of delay will be illustrated and rescheduled times for the disrupted trains will be computed upon the completion of the simulation.

3. DES Model

The sequential framework of the DES model is illustrated in Fig. 1. Object-orientated programming is employed to create the simulation model with Python programming language. In this model, the fixed-increment time-advanced method is adopted and the simulation advances the simulation clock by 1 minute. In the timetables, the train's journey from one station to arrive at another is considered an event. As time advances, the model will continuously check for scheduled events, simulating the seamless operation of all the scheduled train services according to all the timetables over a 24-hour period in a regional railway network.

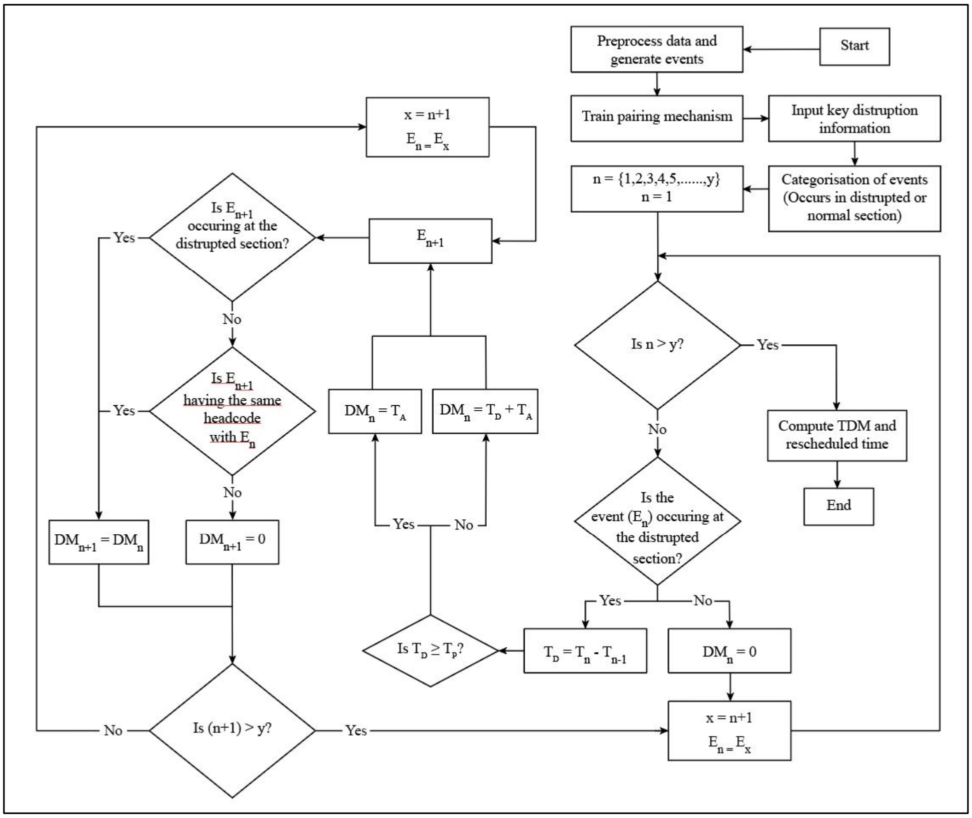

Fig. 1. Sequential framework of the DES model.

Table 1. Annotation for the sequential framework in Fig.1.

Symbol	Description
n	Event number
y	Last event number
E_n	n^{th} event
T_n	Time of the current event E_n
T_{n-1}	Time of the previous event E_{n-1}
T_D	Time difference between T_n and T_{n+1}
T_p	Time taken for a train to traverse the disrupted section
DM_n	Delay minute experienced by n^{th} event
TDM	Total delay minutes
T_A	Additional delay minutes experienced by an event due to speed restriction

In this paper, two distinct railway lines will be included, as illustrated in Fig. 2. Timetable 053 connects Nottingham to Worksop on the East Midlands route, and Timetable 026 connects Leeds to Cleethorpes on the London North East route. The railway lines intersect at Shireoaks East Junction. Both lines consist of a double-track railway, featuring two parallel tracks: one in the up direction and one in the down direction.

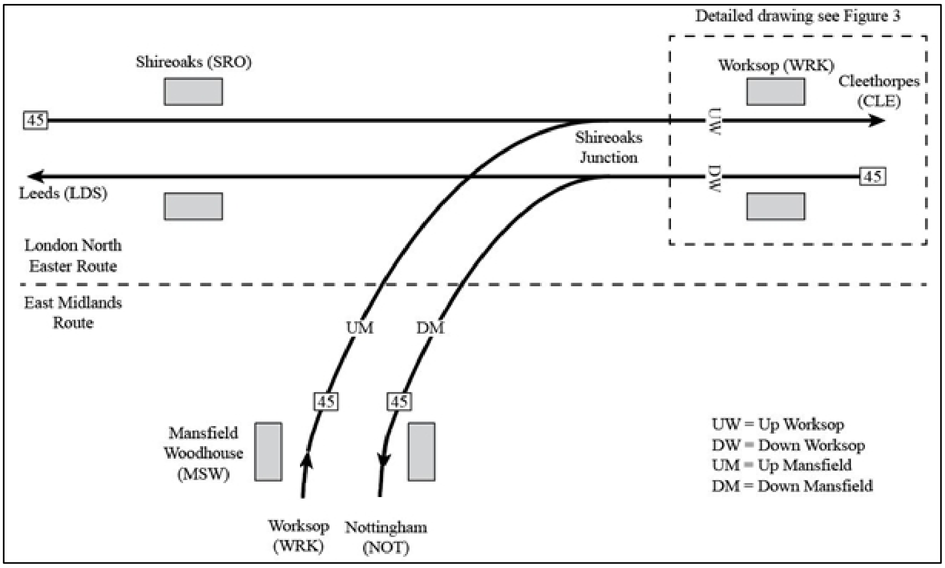

Fig. 2. Multi-line railway network infrastructure layout.

In the existing timetable, the connections between the trains are not specified. Therefore, in this simulation, a mechanism will be implemented to pair trains, enabling the identification of which trains are connected. This allows the determination of which train will also be affected when a train service is altered. The pairing mechanism groups trains based on their departure and termination stations. To determine the subsequent train service for a train in the down-direction timetable, the departure time in the up-direction timetable is correlated with the arrival time in the down-direction timetable. Considering that the number of train services scheduled in both timetables is typically similar, each train is arranged to have a following journey in the opposite direction. Taking the last departure time in the up-direction schedule, any train in the down-direction timetable terminates later than this time is stationed overnight at a depot near the station, ready for the first service in the up-direction timetable the next morning. Once the train services arranged for the next day's trips are identified, the remaining trains in the down-direction timetable are organised and paired up with another train in the up-direction according to their sequence in the timetables.

Key disruption information, including disruption location, disruption start time, disruption duration, type of blockage, and direction, will be inputted into the model. In this paper, a major disruption will be simulated with a disruption duration of 130 minutes, starting at 1330 hours. Specifically, the simulation will involve a partial blockage happening on the up-direction track near Worksop (WRK). A partial blockage is chosen because it involves track switching, allowing the train network to continue operating albeit differently from the regular operations. In contrast, during a full blockage, the entire network comes to a halt, making it less meaningful to simulate as the consequence is already understood: all services are delayed by the total delay time.

During disruption, trains in the up-direction will follow the trajectory shown by the red line in Fig. 3, while the down-direction movement is depicted by the blue line. The disrupted section is determined by locating the nearest crossovers on the up-direction and down-direction tracks around the blockage so that the train can be switched to another line. Next, the distance between the crossovers (D_s) and the restricted speed (V_r) applicable to the disrupted section are determined. By dividing D_s by V_r, the time taken for a train to traverse the disrupted section (T_p) can be calculated. Additionally, the time taken for a train to traverse the disrupted section in normal operating conditions (T_c) can be determined by dividing D_s by normal travel speed (V_d). By calculating the difference between T_c and T_p, the additional delay minutes (T_A) experienced by a train event caused by the restriction of speed, can be determined.

As shown in Fig. 3., in this case, the distance between the two crossovers (D_s) is 2.43 miles. During the disruption, the train's speed is restricted to 15 mph (V_r) on the opposite track of the disrupted one. Consequently, it will take 10 minutes (also taking account of a safety headway between trains) (T_p) for the train to bypass the blockage, including the time required for the switching of the track. The train usually only takes 4 minutes (T_c) to travel through this section at its normal speed. Consequently, the train will experience an additional delay of 6 minutes (T_A).

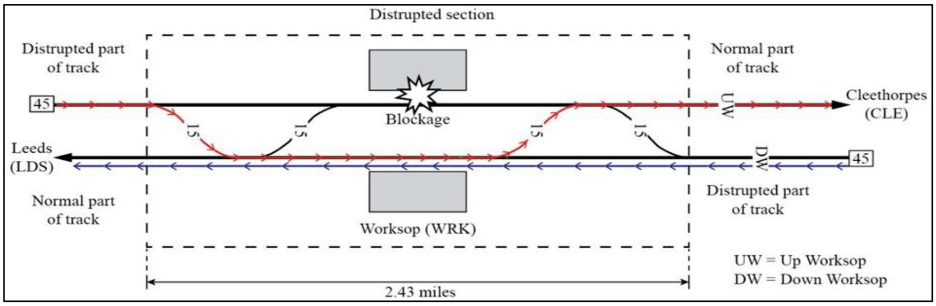

Fig. 3. Railway infrastructure layout of the disrupted section.

Next, events will be categorised as happening in either normal or disrupted sections based on the location relative to the blockage, as illustrated in Fig.3. The normal part is the section of track that lies after the blockage. The train can operate as usual in this area even during disruption, and delays will not continue building up. The disrupted part is the section of the track before the blockage. The train will be disrupted by the blockage during disruption and delays will continuously build up.

It is crucial to note that when a train is travelling in the disrupted section, no other trains are allowed to enter it. They must wait on the track outside the disrupted section and only continue their journey when it is their turn to proceed. For instance, when a train approaches the blocked section 4 minutes after the previous train has entered it, it needs to be delayed by 6 minutes to be allowed to enter the section and continue its journey.

To model this behaviour, the model will calculate the time difference between the current event and the previous event that also took place at the disruption location (T_D). If T_D is smaller than T_p, that train needs to be delayed by T_D on top of T_A. Conversely, if the T_D is greater than or equal to T_p, only T_A will be recorded as delay minutes because the train does not have to wait to enter the disrupted section. It is only delayed by taking a longer time to traverse the disrupted part.

The event with recorded delay minutes that is delayed at the disruption location is a source of delay, which is also the primary delay. For each event with recorded delay minutes, the subsequent events following that event will be examined to determine if they are within the disrupted part of the track. If they are, the delay minutes of these subsequent events will be updated accordingly. Otherwise, if the subsequent event is in the same train service as the current event (with the same headcode), the delay minutes will be updated, too. The model will meticulously examine all the subsequent events to assess whether they are susceptible to reactionary delays stemming from the primary delay, before proceeding to the next source of delay. This reactionary delay is necessary to be considered as all events within the disrupted parts would experience a delay, no matter if they have approached the delay section or not. The delay occurs due to the propagation of the delay originating from the disruption location.

The sum of all delay minutes experienced by each event is then calculated. The total delay minutes (TDM) experienced by a train service is determined by identifying the maximum delay minutes among the events within that train service. The simulation ends after all events have been processed; in this stage of simulation, the propagation of delay is simulated appropriately. The cumulative total delay minutes across the railway network over time will be calculated, to observe the accumulation of delay minutes in the railway network.

Since the objective of this paper is to simulate the propagation of delay throughout the network, with less emphasis on optimising the recovery plan, only reduction of preparation time for the subsequent trains and train cancellation will be included to mitigate the effect of service delay. Regarding the reduction of preparation time, industry practices involve shortening the preparation time based on the urgency and flexibility requirements of the scheduled train services. The flexibility to reduce the preparation time of a trip is greater if the originally scheduled preparation time is long. In this simulation, the next trip's preparation time after a train has completed its previous journey will be halved. The cancellation of the train will be executed strategically based on the results of the simulation.

Finally, due to the complexity of the railway infrastructure layout and practical considerations involved in disruption management, some assumptions have been included in this model:

- the disruption at stations with multiple platforms is not considered;
- the preparation time is halved, with a minimum of 5 minutes, to reduce the delay minutes, and it has been assumed to be sufficient;

- if train services are cancelled or delayed for too long, arrangements for rolling stocks and crews can be made for their scheduled subsequent trips;
- for the computation of cumulative delay time which is not incremental, it is assumed that announcements are made for all the service delays before their departure.

4. Result and Discussion

For validation purposes. the outcomes of the simulation model for Scenario 2, where cancellation of train services is implemented to mitigate delays, are compared to records of real-world delay, specifically incidents 101475 in Tonbridge and 166161 in Yate (*Delay Attribution Board - Network Rail*, n.d.). The results exhibit a consistent pattern, as illustrated in Fig. 4 and Fig. 6. Initially, the primary delay emerges at the onset of the disruption, gradually diminishing as the disruption concludes. However, reactionary delay persists beyond the end of the disruption due to the congestion within the railway network. The reactionary delay gradually diminishes as all disrupted trains complete their journey. This underscores the reliability of the simulation model in accurately simulating the propagation of the primary and reactionary delays based on the key input data of the disruption incident. Furthermore, a comprehensive discussion about the reliability and practicality of the simulation model has been carried out with the Network Performance Manager, who is one of the co-authors of this paper. The co-author commented that this simulation model effectively simulated the propagation of delay, further affirming its credibility.

However, real-world data shows a prolonged propagation of disruption. In both incidents, the observed delay extends significantly beyond the disruption start time. This difference can be attributed to several factors. Firstly, the real-world scenario encompasses a larger and more complex regional network compared to the simulated network, resulting in longer delays due to the increased scale and interconnectedness of railway operations. Additionally, in reality, services are recovered gradually, and disruption often necessitates full track shutdowns for repairs, typically conducted after midnight when the train services have ceased. This extended disruption period contributes to longer reactionary delays. Moreover, real-world scenarios often involve multiple contingency plans to mitigate disruption impacts. Consequently, delay minutes in real-world data may be relatively lower compared to the simulated result due to the effectiveness of the combination of the contingency plans.

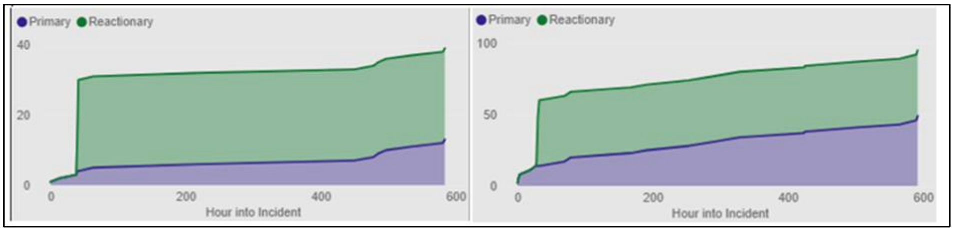

Fig. 4. Primary and reactionary delay minutes by time - Incident 101475 and 166161 (*Delay Attribution Board - Network Rail*, n.d.).

The simulation model is executed according to the scenarios described above, and the result of the simulation of the first scenario can be depicted in Fig. 5. It can be observed that the cumulative delay minutes exhibit a consistent upward trend over time. The increment of delay minutes does not show any sign of slowing down, even after disruption duration. The cumulative primary delay increases over time initially and gradually stabilises after the disruption duration. This behaviour is expected as the primary delay is directly related to the train blockage. Once the train blockage is clear, the delay source diminishes, and the cumulative primary delay stops building up.

In contrast, the cumulative reactionary delay exhibits a slower initial increase. However, it continues to develop even after the disruption duration. This is because the reactionary delay is influenced by the capacity utilisation and the duration of primary delays. Initially, the propagation of reactionary delay is minimal, as fewer trains are waiting to pass the disrupted area, which causes less disturbance to the network. As primary delays accumulate, more train services are affected, causing more delays in the subsequent train services. The cumulative reactionary delay continues to rise even after the blockage is cleared, as the previously delayed trains are still occupying the tracks, causing the scheduled train services to be delayed.

It is worth mentioning that for a major disruption, even if the preparation time for each train before departure is reduced, the propagation of the reactionary delay will not cease. It can be explained by the severity of the disruption. The effect of reducing the preparation time is limited if the delay minutes are long. Due to the setting of this model, the simulation runs without halting, as the delay infinitely propagates. Therefore, the plotted data extends only up to 2045, as the ongoing accumulation of delay time continues without an endpoint and the data range considered is sufficient for studying the propagation of delay.

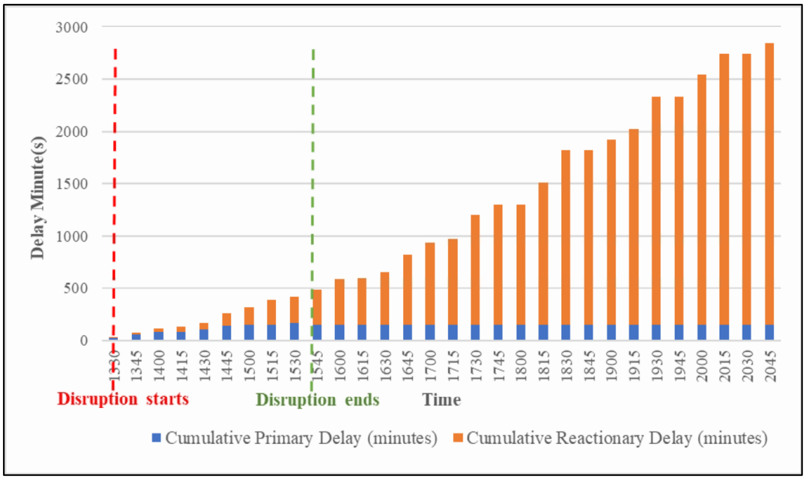

Fig. 5. Cumulative delay minute(s) by time (Scenario 1).

Fig. 6 illustrates the result of the simulation of the second scenario. Based on the result of the first simulation, it becomes evident that the increment of cumulative delay minutes experienced by individual train services does not cease after the clearance of the blockage. With the absence of additional actions, delay minutes cannot be resolved within the network. Due to the significant accumulation of delay minutes in the network, a decision is made to implement the cancellation of trains. Specifically, the trains originally scheduled to operate around the end time of the disruption, from the two directions of each railway line with notably long delay minutes, are cancelled. In this case, 3 trains are cancelled strategically to prevent the further spread of delay throughout the network.

It is discovered that by the cancellation of the trains, the propagation of the reactionary delay can be efficiently halted. The cumulative delay minutes became constant after 1715, which means all train services recovered to their normal state. This proves that the strategic cancellation of trains can serve as a beneficial strategy for the better performance of the railway network as a whole. In addition, if the decision to cancel trains is made much earlier, particularly at the onset of the disruption as suggested by the simulation results, the operators and passengers would have sufficient time to react to the cancellation.

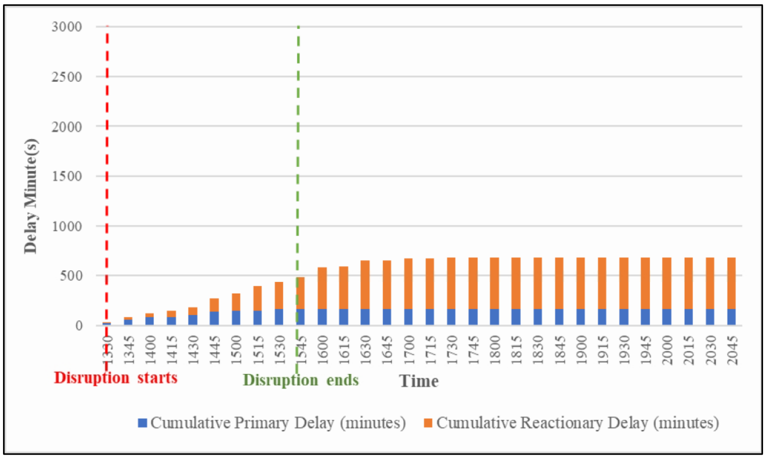

Fig. 6. Cumulative delay minute(s) by time (Scenario 2).

Lastly, the analysis of the train pairing mechanism has revealed that the delay will propagate to the subsequent trip, as shown in Table 2. For instance, if Train EM_2W15 is delayed for 42 minutes, its subsequent trip, EM_2D17 will experience the same amount of delay minutes. When the total delay minutes remains within a manageable range, the delay minutes can be absorbed by reducing the preparation time. However, if the delay minutes become substantial, it is necessary to arrange spare rolling stock and crew for the affected subsequent train services. If the arrangement is impossible, it may result in the necessity of cancelling the subsequent train for the railway network efficiency. The simulation model is run on an Intel i5 with 12 GB RAM, and it takes approximately 30 seconds to complete the simulation. This demonstrates that the DES model is suitable for generating fast responses, which is essential for shortening reaction time to the disruption and preventing further delays.

Table 2. Train Pairing.

Train Headcode	Total Delay Minutes	Subsequent Train Headcode
EM_2D17	12	EM_2W21
EM_2W13	6	EM_2D15
EM_2W14	6	EM_2D14
EM_2W15	42	EM_2D17
EM_2W16	42	EM_2D16
EM_2W18	91	EM_2D18
NT_1L61	85	NT_1L76
NT_1L64	30	NT_1L73
NT_1L65	103	NT_1L80

5. Conclusion and Future Works

In this research, a DES approach that in detail simulates major disruption events and the propagation of reactionary delays throughout the railway network is proposed. The simulation model aims to mimic real-world railway network operations, including factors such as actual infrastructure layout, real timetables, and established industry practices for handling disruption. Two distinct railway lines spanning different routes that intersect at a junction are incorporated into the model to study the railway network interdependencies. The result shows the high degree of interdependencies among different sections of the network as a disruption on a railway line can trigger delays that spread throughout the railway network and last for hours.

The result of the simulation indicates a significant difference between primary and secondary delays. The primary delay ceases shortly after the disruption event ends, whereas the reactionary delay persists if no action is taken to mitigate it. This highlights the importance of addressing the reactionary delay as it will significantly affect the railway network. Therefore, a good decision often depends on minimising the extent of reactionary delay. Besides that, to mitigate the effects of major disruption, the implementation of multiple contingency plans should be considered. Even though train cancellations are normally considered as the last resort in the real-world railway industry, they are efficient in halting the propagation of reactionary delay, which significantly benefits the railway network overall. This simulation model can be used as an advisory tool for network operators, assisting them in managing disruption effectively.

Future work will focus on expanding the scope to include more railway lines in the railway network to gain a more comprehensive understanding of the railway network interdependencies. More constraints will be introduced in this model, including factors such as network infrastructure and rolling stock and crew management to enhance the model's practicality. Furthermore, an optimisation approach shall be developed to automate the selection of mitigation plans, streamlining the decision-making process.

Acknowledgements

The project is supported by Network Rail and the University of Nottingham. The authors gratefully acknowledge the support of these organisations. Appreciation is extended to Ms. Julia Culley for her active involvement and invaluable industrial advice.

References

Carey, M., & Kwiecisiski', A. (1994). STOCHASTIC APPROXIMATION TO THE EFFECTS OF HEADWAYS ON KNOCK-ON DELAYS OF TRAINS (Vol. 28, Issue 4).

Delay Attribution Board - Network Rail. (n.d.). Retrieved April 3, 2024, from https://www.networkrail.co.uk/industry-and-commercial/information-for-operators/network-code/delay-attribution-board/.

Higgins, A., & Kozan, E. (1998). Modeling Train Delays in Urban Networks. In Source: Transportation Science (Vol. 32, Issue 4). https://about.jstor.org/terms.

Hwang, C.-C., & Liu, J.-R. (2010). A Simulation Model for Estimating Knock-on Delay of Taiwan Regional Railway.

Ilalokhoin, O., Pant, R., & Hall, J. W. (2023). A model and methodology for resilience assessment of interdependent rail networks – Case study of Great Britain's rail network. Reliability Engineering and System Safety, 229. https://doi.org/10.1016/j.ress.2022.108895.

Knock-on delays - Network Rail. (n.d.). Retrieved May 6, 2023, from https://www.networkrail.co.uk/running-the-railway/looking-after-the-railway/delays-explained/knock-on-delays/.

Office of Rail and Road. (2023a). Passenger rail performance – April to June 2023.

Office of Rail and Road. (2023b). Table 3124 - Trains planned and cancellations by operator and cause (periodic).

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, Understanding, and Analyzing.

RSSB. (2021). T1154 Enabling Better Planning and Resource Management During Disruption.

RSSB, Network Rail, & UKRRIN. (2021). The-Rail-Technical-Strategy.

Steer Group, Andy Castledline, & RSSB. (2020). Enabling Better Planning and Resource Management During Disruption. www.sparkrail.org.

Tendeloo, Hans Vangheluwe, & Romain Francesshini. (2019). An Introduction to Modeling and Simulation with Python (DEV).

Vansteenwegen, P., Leuven, K. U., Sels, P., Dewilde, T., & Cattrysse, D. (2013). A Passenger Knock-On Delay Model for Timetable Optimisation Optimal Resource Allocation and Budgeting in Libraries View project Peter Sels Logically Yours Dirk Cattrysse KU Leuven A Passenger Knock-On Delay Model for Timetable Optimisation. https://www.researchgate.net/publication/282211923.

Zou, H., & Liu, S. (2021). Design and Research of Wuhan Urban Railway Network Simulation Calculation Information System Utilizing Big Data. Journal of Physics: Conference Series, 1982(1). https://doi.org/10.1088/1742-6596/1982/1/012143.