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An Event-Based Simulation Modelling for Evaluating the Operating Practice of the West Midlands Metro

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ABSTRACT

The rapid expansion of the metro network, driven by urbanisation and a heightened focus on environmental sustainability, underscores the need for efficient and sustainable public transportation systems. This study utilises the West Midlands Metro system as a case study to investigate operational efficiency and utilisation challenges that are common across metro networks globally. Employing advanced simulation modelling with SIMUL8, this research evaluates the existing timetables and utilisation rates of the West Midlands Metro to uncover inefficiencies and untapped potential. Various scenarios, including increased service frequencies and disruptions at high-traffic stations, were simulated to provide useful insights for optimising metro operations. Findings revealed that increasing service frequency from every 10 minutes to every 5 minutes enhanced utilisation levels and boosted the total number of completed services. Meanwhile, disruptions at major stops resulted in a reduction in utilisation in a negligible range. These results demonstrate that improved service frequency significantly bolsters operational efficiency and showcases resilience to disruptions with minimal impact on overall performance. As to future research, the study suggests that implementing adaptive scheduling through AI-driven maintenance and infrastructure improvements can further elevate the efficiency and passenger experience of metro operations.

KEYWORDS

metro system evaluation; simulation modelling; utilisation analysis; scenarios.

1. INTRODUCTION

Metro system growth in recent years has been an immediate response to expanding urbanisation trends, environmental concerns and the worldwide pursuit of higher living standards. The UITP World Metro Figures 2021 [1] study states, there was a notable 25% increase in worldwide metro infrastructure between 2018 and 2020. Shinde and Marinov [2] emphasised how automation technology integration and the growth of metro rail transportation networks are having an increasingly significant impact on metro operations globally. In the context of growing their networks and embracing automation, metro services throughout the world sometimes struggle to strike a healthy balance between capital costs and levels of utilisation. Investigating the unrealised potential of the current metro networks is essential to closing this gap. This investigation provides opportunities for additional development in addition to helping to improve system utilisation. To contribute to this discussion and address the need for further in-depth study, it is necessary to assess the actual performance of metro systems. Comprehensive timetable analysis and utilisation level assessment yield insightful information. This rationale highlights how important it is to evaluate the schedules of the West Midlands Metro by creating a simulation model since this is a crucial first step towards comprehending and enhancing the functioning of the metro system.

1.1 Motivation

The rapid rate of change in urban transportation necessitates the ongoing reassessment and evaluation of metro systems. As urbanisation accelerates and environmental concerns grow, the need to provide efficient, sustainable and responsive public transportation networks becomes more pressing. Within this evolving setting, the West Midlands Metro system serves as a microcosm of the larger issues that metro operators face worldwide.

This research derives from the need to solve a recurrent difficulty encountered by metro systems across the world: striking a healthy balance between capital investments and operational utilisation. Utilisation levels, in particular, refer to the proportion network's capacity that is actively used over a certain period. It reflects how well a metro system component is handling the flow of metro services compared to its maximum capacity. A high utilisation level suggests that a station or network is operating close to its full capacity, while a low utilisation level indicates underuse. Utilisation rates, on the other hand, represent the ratio of the actual services completed to the maximum possible services that could be completed within a given timeframe. It provides a broader view of system-wide efficiency, measuring how much of the system's potential is being used for operations.

While metro networks grow in response to increased urbanisation, optimising their operating dynamics remains a top priority. The need to uncover latent potential within current metro systems by examining utilisation levels and operating procedures becomes clear.

1.2 Objectives

This research aims to analyse the operating dynamics of the West Midlands Metro system using simulation modelling, with the following objectives in particular:

— Assess the existing timetables and utilisation levels of the West Midlands Metro system to discover underutilisation and inefficiencies.
— Identify spatial inconsistencies and system-wide operating issues in the metro network.
— Provide useful information and recommendations to improve the West Midlands Metro's efficiency, reliability and passenger experience.
— Inform decision-making processes for future infrastructure development and operational improvements in the West Midlands Metro and similar metro systems across the globe.

By achieving these objectives, this research endeavours to catalyse continuous improvement within the West Midlands Metro system and contribute to the advancement of best practices in urban rail transportation networks worldwide.

1.3 Research question

How can the operational efficiency and utilisation of the West Midlands Metro system be evaluated through simulation modelling, and what specific interventions can address spatial inconsistencies and improve service reliability?

By utilising advanced simulation modelling techniques, specifically with the SIMUL8 software, it is possible to identify and quantify underutilisation and inefficiencies within the West Midlands Metro system. Furthermore, targeted interventions based on simulation results can significantly enhance operational efficiency, reduce spatial inconsistencies and improve overall service reliability and passenger satisfaction.

This research analyses metro system performance by evaluating the existing timetables and utilisation levels through detailed simulation, identifying key areas for improvement and proposing specific operational changes. The expected outcome is that these changes, when implemented, will lead to measurable improvements in the metro system's performance metrics.

1.4 Paper organisation

Section 1 introduces the study, including an overview of the West Midlands Metro. Section 2 discusses relevant literature on simulation modelling in metro systems. Section 3 outlines the methodology, detailing the framework, attributes and other aspects used to construct the SIMUL8-based simulation model. Section 4 presents the results obtained from the simulation model. This includes the analysis of the current operational dynamics (Scenario 0), the impact of increased service frequency (Scenario 1) and the effects of introducing disruptions at major stops (Scenario 2). Each scenario is analysed in detail, providing insights into service completion rates and utilisation levels across the metro network. Section 5 concludes the paper by summarising the main findings of the study and discusses the key insights derived from the simulation-based analysis. It interprets the results and provides actionable recommendations.

2. METRO SYSTEM CHARACTERISTICS AND SIMULATION MODELLING

Metro systems are vital components of urban infrastructure, often requiring detailed analysis to ensure operational efficiency and optimal resource utilisation. Simulation modelling provides a powerful tool to evaluate various operational scenarios and uncover inefficiencies, allowing for informed decision-making in the development of metro services.

2.1 Overview of the West Midlands metro operations

The West Midlands Metro is a tram route in the United Kingdom that links the cities of Wolverhampton and Birmingham. Wolverhampton St. George's and Edgbaston are currently served by a tram line [3]. The West Midlands Metro service includes the following stations (*Table 1*):

Table 1 – List of stops on the West Midlands Metro line. Referred from West Midlands Metro, 2023

Towards Wolverhampton	Towards Birmingham
Edgbaston (Zone 1)	**Wolverhampton St George's** (Zone 4)
Five Ways (Zone 1)	**The Royal** (Zone 4)
Brindley Place (Zone 1)	**Priestfield** (Zone 3&4)
Library (Zone 1)	**The Crescent** (Zone 3)
Town Hall (Zone 1)	**Bilston Central** (Zone 3)
Grand Central (Zone 1)	**Loxdale** (Zone 3)
Corporation Street (Zone 1)	**Bradley Lane** (Zone 3)
Bull Street (Zone 1)	**Wednesbury Parkway** (Zone 3)
St Chads (Zone 1)	**Wednesbury Great Western Street** (Zone 3)
St Pauls (Zone 1)	**Black Lake** (Zone 2&3)
Jewellery Quarter (Zone 1&2)	**Dudley Street Guns Village** (Zone 2)
Soho Benson Road (Zone 2)	**Dartmouth Street** (Zone 2)
Winson Green Outer Circle (Zone 2)	**Lodge Road** (Zone 2)
Handsworth Booth Street (Zone 2)	**West Bromwich Central** (Zone 2)
The Hawthorns (Zone 2)	**Trinity Way** (Zone 2)
Kenrick Park (Zone 2)	**Kenrick Park** (Zone 2)
Trinity Way (Zone 2)	**The Hawthorns** (Zone 2)
West Bromwich Central (Zone 2)	**Handsworth Booth Street** (Zone 2)
Lodge Road (Zone 2)	**Winson Green Outer Circle** (Zone 2)
Dartmouth Street (Zone 2)	**Soho Benson Road** (Zone 2)
Dudley Street Guns Village (Zone 2)	**Jewellery Quarter** (Zone 1&2)
Black Lake (Zone 2&3)	**St Pauls** (Zone 1)
Wednesbury Great Western Street (Zone 3)	**St Chads** (Zone 1)
Wednesbury Parkway (Zone 3)	**Bull Street** (Zone 1)
Bradley Lane (Zone 3)	**Corporation Street** (Zone 1)
Loxdale (Zone 3)	**Grand Central** (Zone 1)
Bilston Central (Zone 3)	**Town Hall** (Zone 1)
The Crescent (Zone 3)	**Library** (Zone 1)
Priestfield (Zone 3&4)	**Brindley Place** (Zone 1)
The Royal (Zone 4)	**Five Ways** (Zone 1)
Wolverhampton St George's (Zone 4)	**Edgbaston** (Zone 1)

There is a light rail line at the location that runs through the streets of the urban regions in a single line. Moreover, it has facilitated the accessibility of traditional railway networks connecting various urban and rural areas. Based on the timetable provided by the West Midlands Metro for the year 2023, the metro rail system adheres to a regular interval of 10 minutes during periods of high demand, often referred to as peak hours. Conversely, during periods of lower demand, known as nonpeak hours, including Sundays, the metro rail runs at intervals of 15 minutes.

Table 2 – System summary for tram vehicles in England in the year ending March 2022
Referred from Government of the United Kingdom 2022

	Length of system (miles)	Number of stops	Number of tram vehicles	Average journey length (miles)
England	219	410	536	4.2
London systems	41	84	184	3.2
Docklands Light Railway	24	45	149	3.2
London Trams	17	39	35	3.2
England outside London systems	178	326	352	5.3
Nottingham Express Transit	20	50	37	4.1
West Midlands Metro	14	28	29	6.7
Sheffield Supertram	21	50	32	4.0
Tyne and Wear Metro	48	60	89	5.4
Manchester Metrolink	64	99	137	6.5
Blackpool Tramway	11	39	28	2.7

Table 2 presents comprehensive data pertaining to the system's summary for tram vehicles in England, including the system's length, the number of trams and the number of stations. According to *Table 2*, the system has a total operational distance of 14 miles, including 28 designated stations, and is facilitated by a fleet of 29 tram vehicles, the mean distance covered throughout the journey is 6.7 miles. The data reveal that the metro system in England spans a total distance of 219 miles, with the West Midlands Metro and its associated lines accounting for a coverage of 14 miles. Furthermore, it has 29 out of the total 536 tram vehicles in England, as a result establishing itself as a significant component of the tram network in the nation, outside London [4].

2.2 Introduction to simulation modelling in metro systems

Public transportation networks like metro systems are highly complex with multiple interdependent components and variables. Passenger demand, train schedules, fleet availability, staffing levels, infrastructure maintenance, etc. all impact each other in determining the system performance. Transportation planners therefore face major challenges in analysing and optimising these large-scale networks.

Simulation modelling provides a vital virtual experimentation capability to overcome these challenges. By developing computer models of transportation systems, planners can mimic real-world functioning and test various changes and scenarios. For instance, a metro line simulation model makes it possible to experiment with train frequency, carriage capacity, signalling systems, maintenance planning, etc. The model outputs quantify the impact of these changes on key metrics like passenger waiting times, congestion levels, equipment failures, etc. before actual implementation.

This simulation-based analysis is invaluable for metro networks given their scale, complexity and passenger volumes. Previous studies have leveraged event-based simulation to analyse metro system operations. Singhania and Marinov [5] developed a SIMUL8-based simulation model to study the utilisation levels of a railway line segment in an urban area, evaluating the impacts of incorporating additional freight trains. Motraghi and Marinov [6] used an ARENA-based event simulation to analyse the potential of urban freight transportation by rail. Stoilova and Stoev [7] also used an ARENA-based simulation modelling approach complemented by analytical modelling to study a metro system performance using a real-world case, i.e. Metro Sofia. It was demonstrated that the models proposed and implemented help better organise the metro system operation (the term "subway" is used) and facilitate interaction with other modes of public transport. Wales and Marinov [8] constructed a SIMUL8 simulation model to investigate delay mitigation tactics for the Tyne and Wear Metro system. Furthermore, Abbott and Marinov [9] employed event-based simulation to design a rail interchange yard that can facilitate the integration of high-speed and conventional rail networks.

These studies demonstrate the power of simulation modelling in uncovering insights about metro system performance, optimisation opportunities and mitigation strategies – all of which are crucial for improving service quality and efficiency. The visual, animated and data-driven simulation capabilities help develop an improved understanding of interactions between various metro line components. Simulation thereby empowers transportation planners to make informed, analytical decisions about improving metro operations.

In the context of the West Midlands Metro, simulation modelling can be leveraged to evaluate improvement strategies for this developing network by analysing its operations and identifying areas for enhancement, in line with the objectives of the current research.

2.3 Recent advances in metro system simulation

In the past several years, significant advancements have been made in metro system simulation, emphasising resilience, energy efficiency, AI integration, real-time operation management and enhanced simulation tools. These innovations are crucial for optimising metro operations and ensuring robust, efficient and sustainable urban transportation networks.

Recent studies have significantly focused on enhancing the resilience of metro systems against environmental disruptions, particularly floods. Shi et al. [10] proposed a three-stage PEL (prevention, response, learning) resilience enhancement framework for urban metro systems. This framework integrates resilience strategies across multiple dimensions – natural, physical, social, management and economic – using system dynamics to simulate and evaluate the impacts of these factors. The study's findings highlight the need for comprehensive resilience strategies to ensure robust metro operations under adverse conditions [11].

Yu et al. [11] introduced a dynamic train density model aimed at optimising urban rail systems during peak operation periods. This model incorporates a multi-train circuit with a bilateral power supply, allowing real-time adjustments based on train density. Utilising actual operation data and spatial electrical data, the model enhances simulation accuracy, particularly in managing voltage fluctuations and optimising regenerative braking energy (RBE) utilisation. This approach not only improves operational efficiency but also significantly contributes to energy-saving initiatives in urban rail systems [11].

The simulation of real-time operations, particularly integrating passenger and light freight transport within metro networks, has been another area of advancement. Studies have explored holistic concepts of metro-based urban underground logistics systems (M-ULS), integrating passengers and urban freight transport in a unified simulation framework. This approach helps evaluate operational decisions, improve urban logistics efficiency and improve metro infrastructure utilisation [8, 11].

The integration of artificial intelligence (AI) and machine learning (ML) in metro system simulations has gained traction as well, offering predictive and adaptive capabilities. Advanced AI systems can analyse real-time data to predict maintenance needs, optimise scheduling and manage disruptions more effectively. These systems enhance overall responsiveness and efficiency, ensuring higher service reliability and passenger satisfaction [8, 11].

The development and refinement of simulation tools and platforms, such as SIMUL8 and MATLAB/Simulink, have significantly improved. These tools now support more complex and detailed simulations, incorporating factors like energy consumption, train schedules and emergency response scenarios. The enhanced capabilities of these platforms facilitate more accurate modelling and analysis, aiding in strategic planning and operational management of metro systems [11].

2.4 Using SIMUL8 for metro operation analysis

Deep learning techniques are currently in use for the predictive monitoring of business processes. The use of simulation can contribute to this deep learning process by making it possible to generate whole traces for the execution of business processes or entire event logs, which allows the models to be open for process simulation [12]. The design of the simulation models depends on the quality of the data that have been provided and on conducting a comprehensive analysis of the system.

Simul8 is software that uses computer simulation for analysing managerial issues [13]. It is caused by the inability to use standard analytical tools since the real processes are complex. The logistical and production problems in reality often align with the simulations due to the dynamic and probabilistic nature of the process.

The production process is usually a discrete event simulation [14]. However, the lack of flexibility and the lack of an interface for effectively inputting data were issues with the use of this model [15]. This can be used as a forecasting model for making decisions regarding the adoption of automation.

3. METHODOLOGY

In the field of transportation research, the methodology used for simulation modelling is critical in assuring the quality and dependability of the results. Drawing on known approaches, this research employs a simulation approach to examine and evaluate the present schedules and utilisation levels of the West Midlands Metro system. The technique was influenced by the work of Potti and Marinov [5], who successfully used simulation modelling to analyse the West Midlands Metro's ridership increase. However, the study may benefit from a more in-depth examination of the simulation approach used and the practical suggestions produced from the analysis. Providing detailed explanations of the simulation process and elaborating on the study's applications would both increase the study's impact and reinforce its relevance in the rapidly changing field of transportation studies, especially in light of the years that have passed since its publication in 2020.

3.1 Framework

In order to evaluate the operational performance of the West Midlands metro line and provide a foundation of knowledge on its functionality, a simulation model of the present metro line in the West Midlands region is constructed using the SIMUL8 software platform.

The main aim of this study is to assess and graphically illustrate the operating dynamics of the West Midlands metro line. The construction of the model relies on the use of secondary data. This model was developed based on sources like the official websites of the West Midlands, scholarly publications, reports and peer-reviewed studies.

3.2 Foundation

To successfully fulfil the intended objectives, it is essential to conduct a thorough examination of the current West Midlands metro line. To achieve this objective, a comprehensive assessment is carried out through a visual simulation modelling experiment.

The use of SIMUL8 computer software, a specific tool designed for event-based simulation, is employed for experimentation. The effective development of a simulation network model using a queueing network framework has been achieved, *Figure 1*.

The interconnected queueing systems within queueing networks demonstrate a reciprocal interplay and impact, thereby yielding a comprehensive depiction of the combined effects of individual stations and all metro operations within the network.

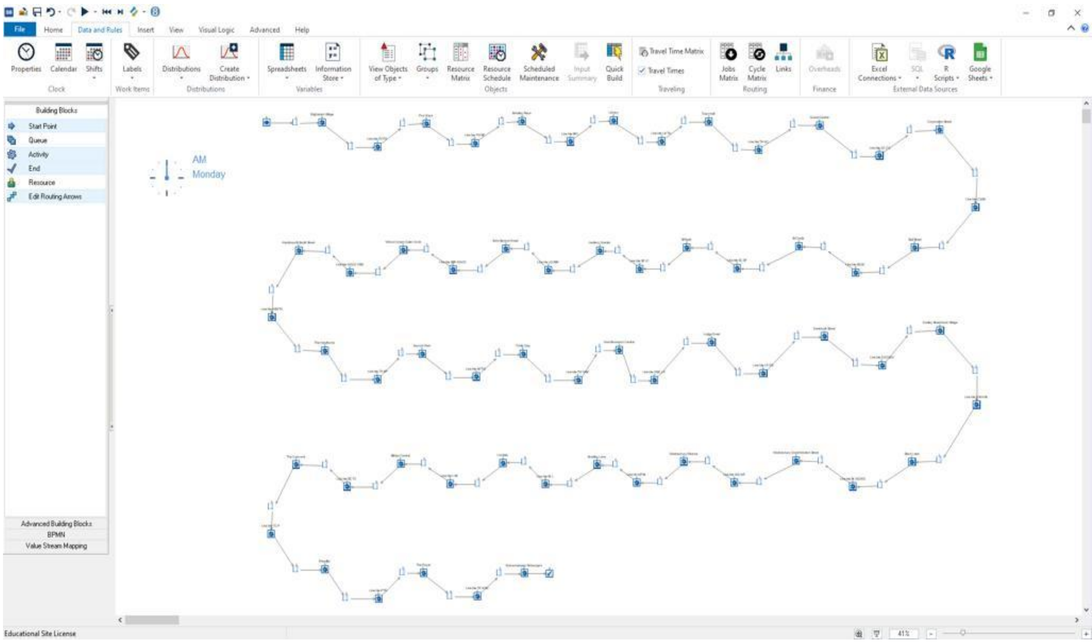

Figure 1 – Simulation model of the West Midlands Metro

3.3 Attributes

A set of activities and queues are used to build a simulation model of the West Midlands metro network.

Each “activity” represents a station on the West Midlands metro line. Each station has a fixed service time of 1 minute (*Figure 2*).

The “queues” work as the storage area. They replicate where the trams are held while waiting to be processed by a given component of the metro network (*Figure 3*).

In between two stations, an additional activity and queue are introduced to replicate the operating processes of the metro system. Each additional activity is named “Line between X and Y”, where X and Y indicate before and after stations respectively (*Figure 4*). The time between stations is an input based on the current metro timetable, as detailed in *Table 3*. This ensures that the simulation accurately reflects the real-world operation times.

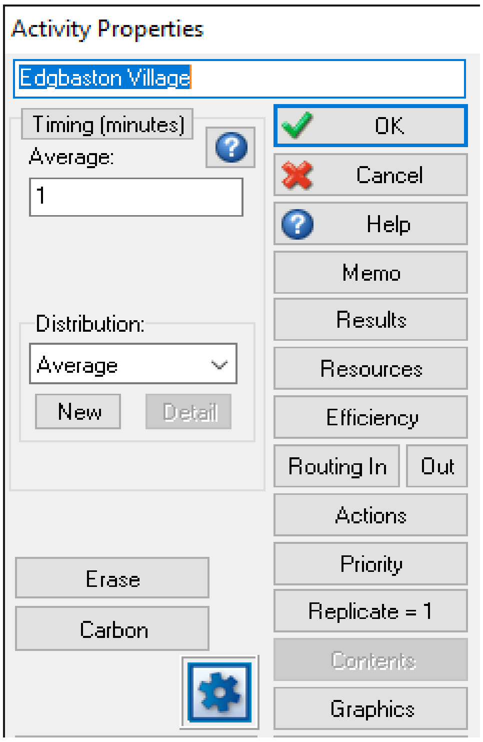

Figure 2 – Attribute: Activity of the first service

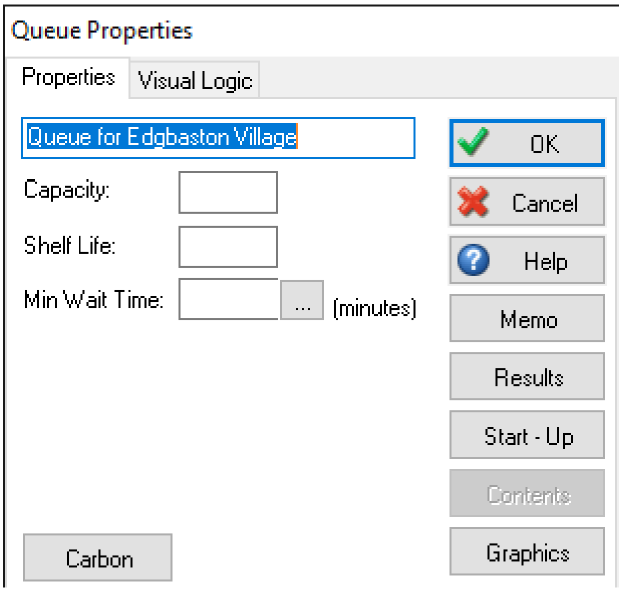

Figure 3 – Attribute: Queue of the first service

Table 3 – West Midlands metro/travel time between stations, 2023. Referred to West Midlands Metro timetable

Stations	Service		Stations	Service	
Edgbaston	0515		Kenrick Park	0543	
		2			1
Five Ways	0517		Trinity Way	0544	
		2			1
Brindley Place	0519		West Bromwich Central	0545	
		2			1
Library	0521		Lodge Road	0546	
		3			1
Town Hall	0524		Dartmouth Street	0547	
		2			1
Grand Central	0526		Dudley Street Guns Village	0548	
		2			1
Corporation Street	0528		Black Lake	0549	
		1			3
Bull Street	0529		Wednesbury Great Western Street	0552	
		2			4
St. Chads	0531		Wednesbury Parkway	0556	
		2			3
St. Pauls	0533		Bradley Lane	0559	
		1			1
Jewellery Quater	0534		Loxdale	0600	
		2			2
Soho Benson Road	0536		Bliston Central	0602	
		2			1
Winson Green Outer Circle	0538		The Crescent	0603	
		2			1
Handsworth Booth Street	0540		Priestfield	0604	
		1			3
The Hawthorns	0541		The Royal	0607	
		2			2
			Wolverhampton St. George’s	0609	
			TOTAL		54

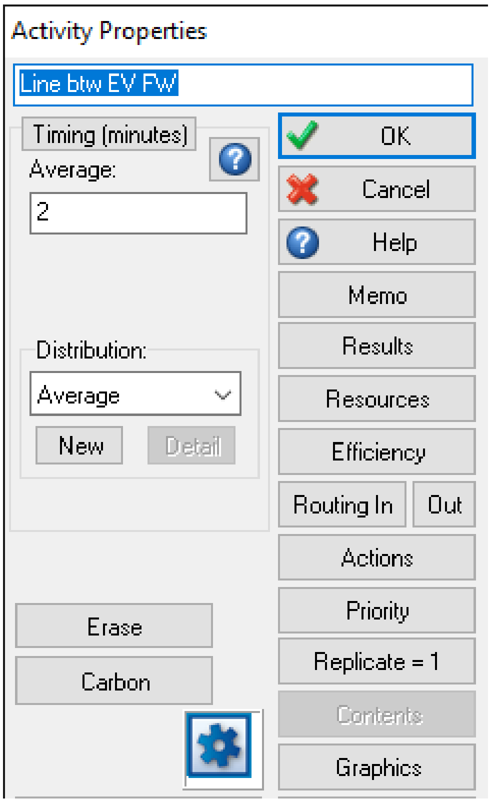

Figure 4 – Attribute: In between activity of the 1st and 2nd service

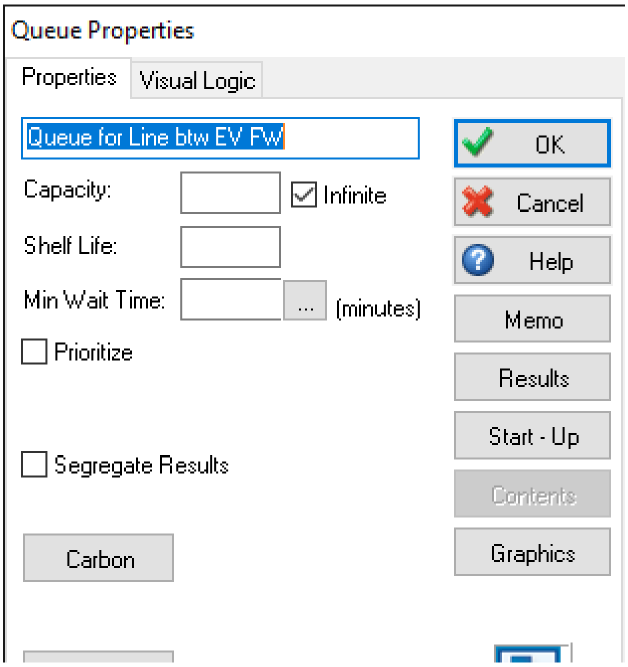

Figure 5 – Attribute: In between queue for the 1st and 2nd services

When a tram leaves the metro network, its service is assumed to have terminated. In SIMUL8, this event is replicated by an attribute called "Work End Point" (*Figure 6*).

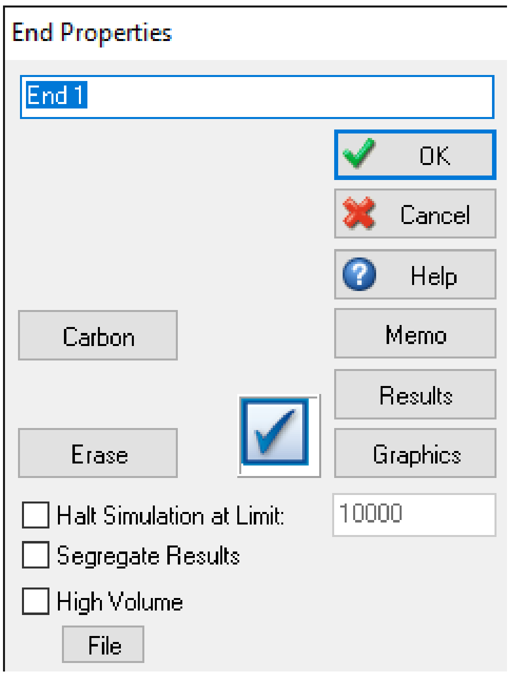

Figure 6 – Attribute: Work End Point

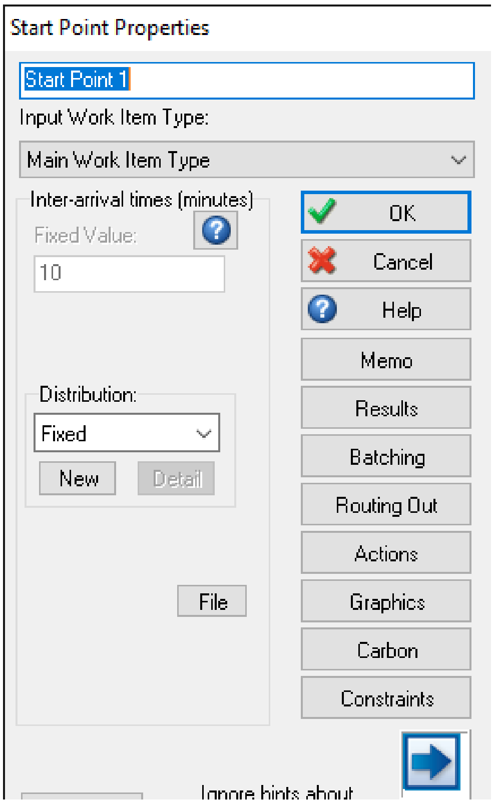

Figure 7 – Attribute: Work Start Point

To generate the work items (in our case, the tram), an attribute called "Work Start Point" is employed (*Figure 7*). The start point is characterised by an arrival pattern. The arrival pattern may be subordinated to a familiar theoretical distribution, an empirical distribution or a time-dependent distribution.

3.4 Arrival pattern

In this study, the arrival pattern is set as a "fixed" and "schedule" distribution. This choice is made in order to accurately reflect the operational dynamics of the current West Midlands metro line. To achieve this, the precise outcomes are obtained by adhering to the existing metro timetable, as depicted in *Table 4*. By employing this approach, a model is constructed that faithfully replicates the intricate functioning of the current West Midlands metro line.

Table 4 – Edgbaston departures, referred to West Midlands Metro timetable

		Minutes after midnight
1st	515	315
2nd	525	325
3rd	535	335
4th	545	345
5th	555	355
6th	605	405
7th	615	415
8th	625	425
9th	635	435
10th	645	445
11th	655	455
12th	705	505
13th	715	515
14th	725	525
15th	735	535
16th	745	545
17th	755	555
18th	805	605
19th	815	615
20th	825	625
21st	835	635
22nd	845	645
23rd	855	655
24th	905	705
25th	915	715
26th	925	725
27th	935	735
28th	945	745
29th	955	755
30th	1005	805

3.5 Routing

The specification of work item routing within the network is accomplished through the use of "Workflow Arrows". These arrows serve the purpose of indicating the various paths that trams traverse as they progress through the components or subcomponents of the metro network. These paths include the movement from the Work Entry Point to a queue, from a queue to an activity, from an activity to an in-between queue, from an in-between queue to an in-between activity, and from an in-between activity to the subsequent queue, and so on. The Workflow Arrows thus play a crucial role in delineating the routing of work items within the network.

In the West Midlands Metro simulation model, in-between queues and in-between activities are introduced to replicate the operating processes of the metro system. These elements simulate the travel time and interactions between stations, even though the system does not have alternative routes. This approach allows for a detailed analysis of tram movements and potential bottlenecks within the single-line network. Each in-between activity represents the travel time between two stations based on the current metro timetable, ensuring the model accurately reflects real-world operation dynamics. This level of detail is essential for identifying and addressing inefficiencies in the metro system's operation.

3.6 Clock

The time aspect of a simulation is established and regulated by a parameter known as the "clock" (*Figure 8*). The initiation of the simulation is established to commence precisely at the time-based period of midnight (00:00). The time frame extent of a single per-day cycle is posited to be approximately 9 units of time. It is crucial to note that the data under consideration in this study were gathered over the course of one single day, thereby confining the scope of the investigation to this specific temporal domain. The designated duration for the warm-up period has been established as 300 minutes, as determined through the following calculation:

Warm-up period – 5 hrs. × 60 min =300 min

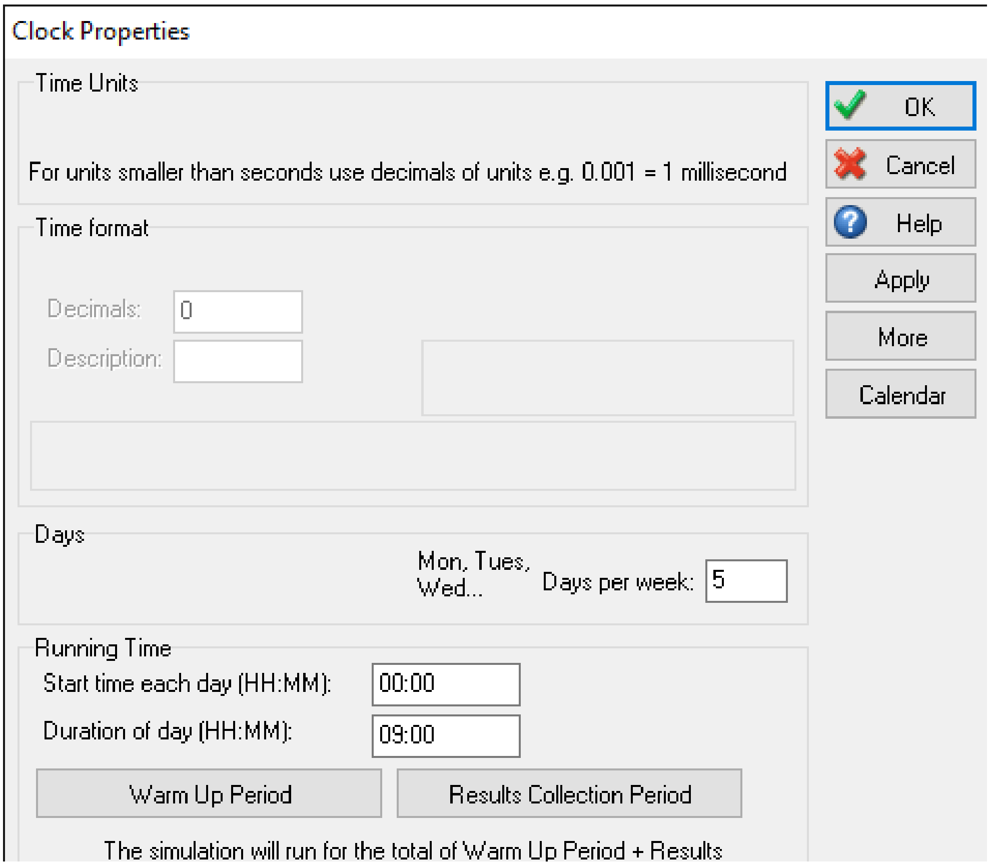

Figure 8 – Clock settings

3.7 Collection of results

The data obtained in this study are derived from a series of replications, also referred to as multiple runs, thereby constituting a collection of trials. The establishment of the number of replications encompassed within one single trial is facilitated by means of an option denoted as "conduct trial".

3.8 Measures of system performance (MOPs)

Aspects used to measure system performance are the total number of services completed at each station for the observed period, the number of trams in a given queue, the utilisation levels of the network subcomponents and the utilisation rates of the system.

3.9 Limitations

— The observation period is restricted to just peak hours in the morning.
— Only one-way transit, i.e. from Birmingham to Wolverhampton station, is under observation.
— The study focuses solely on the weekday schedule.

4. RESULTS

For the purposes of this discussion, the following scenarios were developed and analysed.

4.1 Scenario 0: Analysis of current operational dynamics

With the help of the literature review and simulation model, the analysis of the current West Midlands metro system produced useful insights into its operational dynamics. The results obtained from the simulation model, as a form of validation of accuracy, have been verified through the actual West Midlands Metro timetable. This was done to ensure that the results produced by the simulation model developed were realistic and that they aligned with the current timetable. The simulation model showed the exact same values confirming accuracy. Additionally, different scenarios were evaluated to confirm the robustness of the findings.

The various measures of system performance (MoPs) are demonstrated in *Figures 9, 10, 11* and *12*.

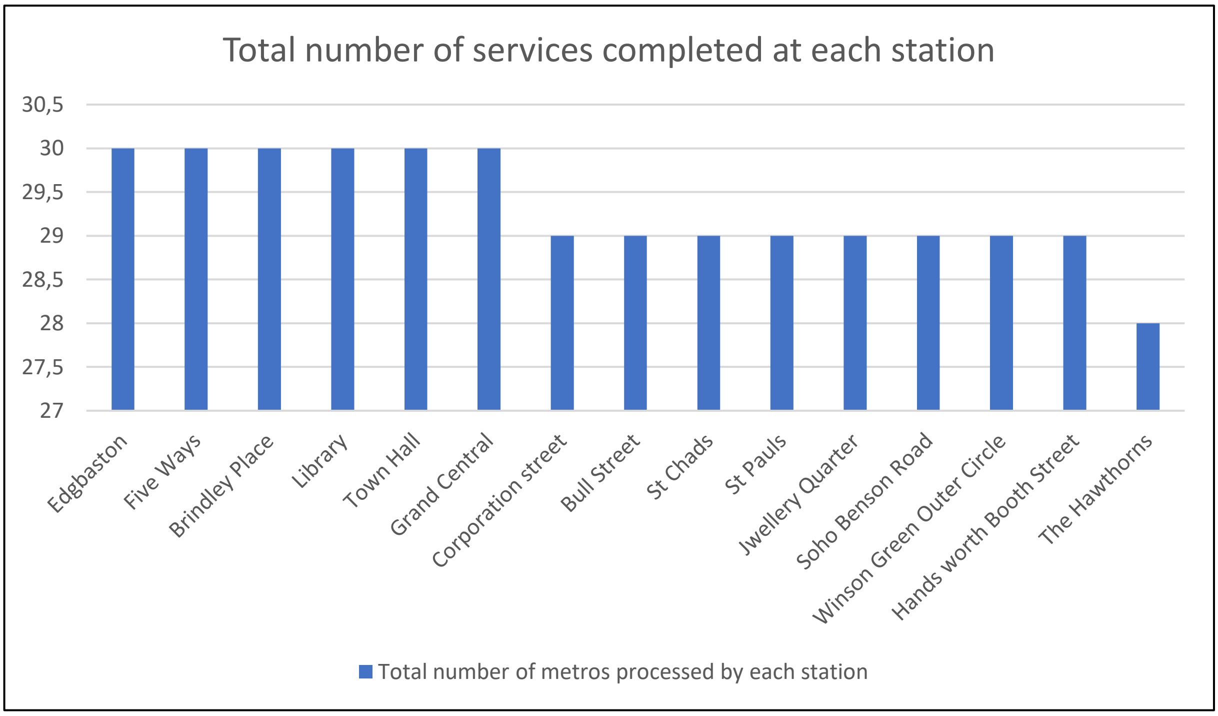

Figure 9 – Total number of services completed at each station for the observed period

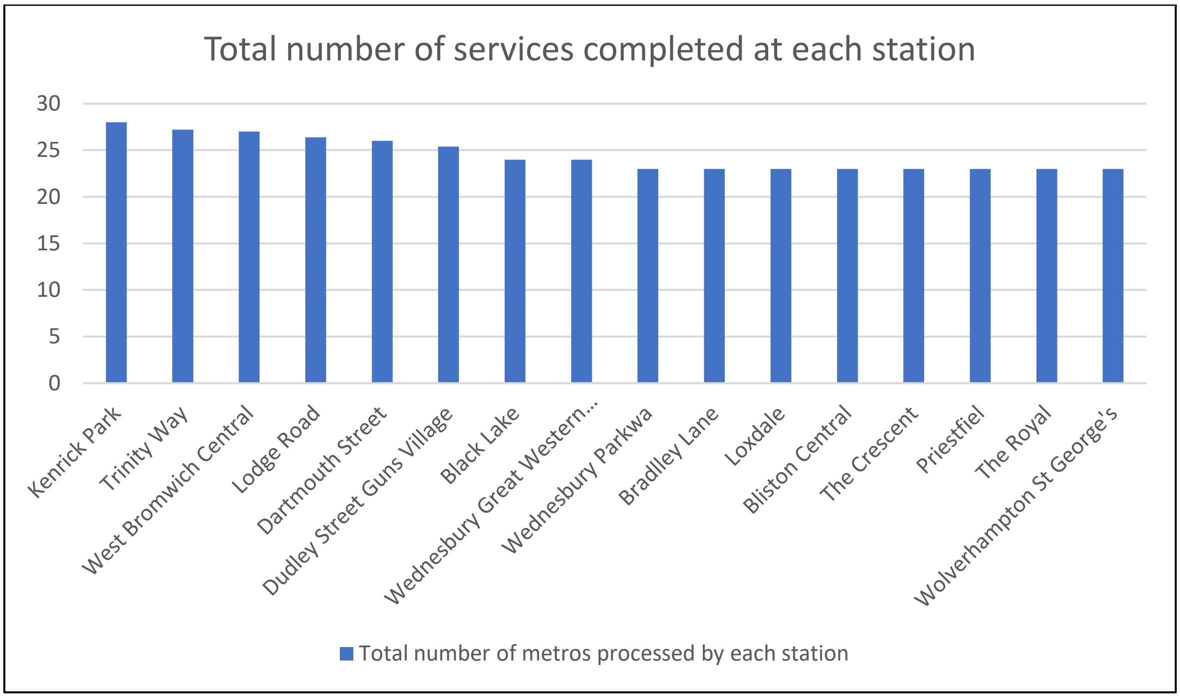

Figure 10 – Total number of services completed at each station for the observed period

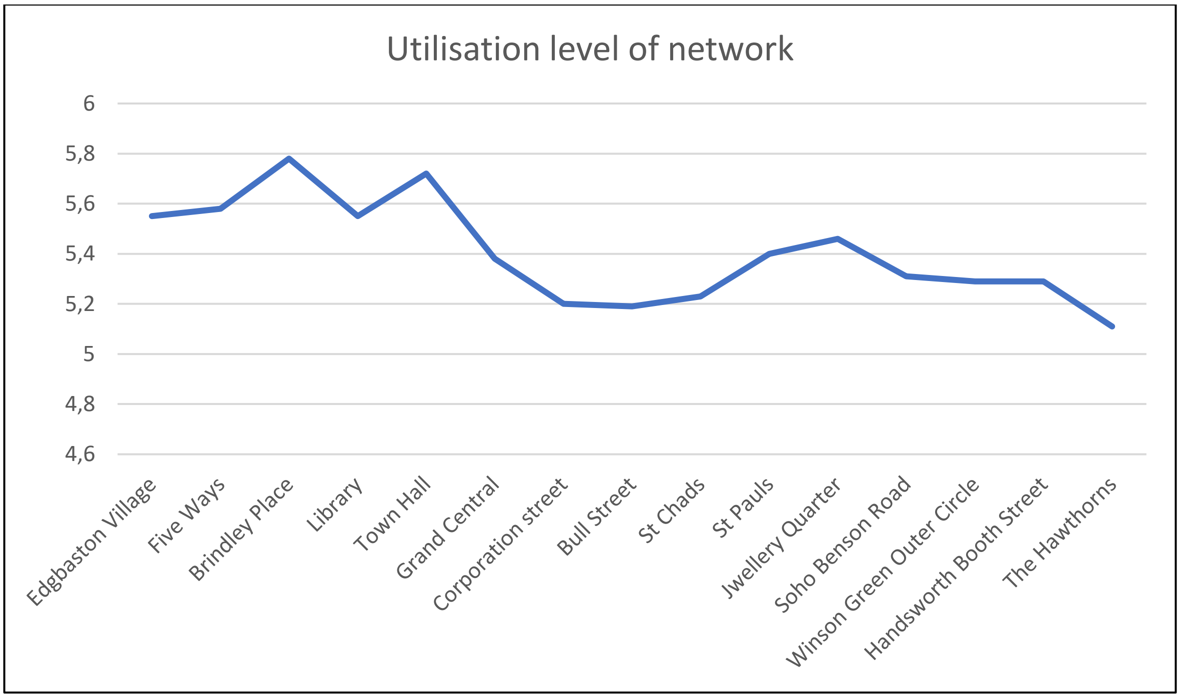

Figure 11 – Utilisation level of the network at each station

These results provide a nuanced understanding of service performance, utilisation levels and system-wide efficiencies, paving the way for targeted interventions to enhance the metro network's functionality and ultimately passenger experience.

— Fluctuating Service Counts: *Figures 9* and *10* depict the total number of services completed at each station throughout the observed period. A notable observation is the variability in service counts across different stations, indicative of spatial disparities in service delivery. Stations from Edgbaston to Grand Central exhibit relatively higher and uniform service counts, suggesting robust operational performance and adequate resource allocation. Conversely, stations from the Hawthorns to Wolverhampton St. George's register lower and fluctuating service counts, signalling potential areas for improvement in service consistency and frequency.

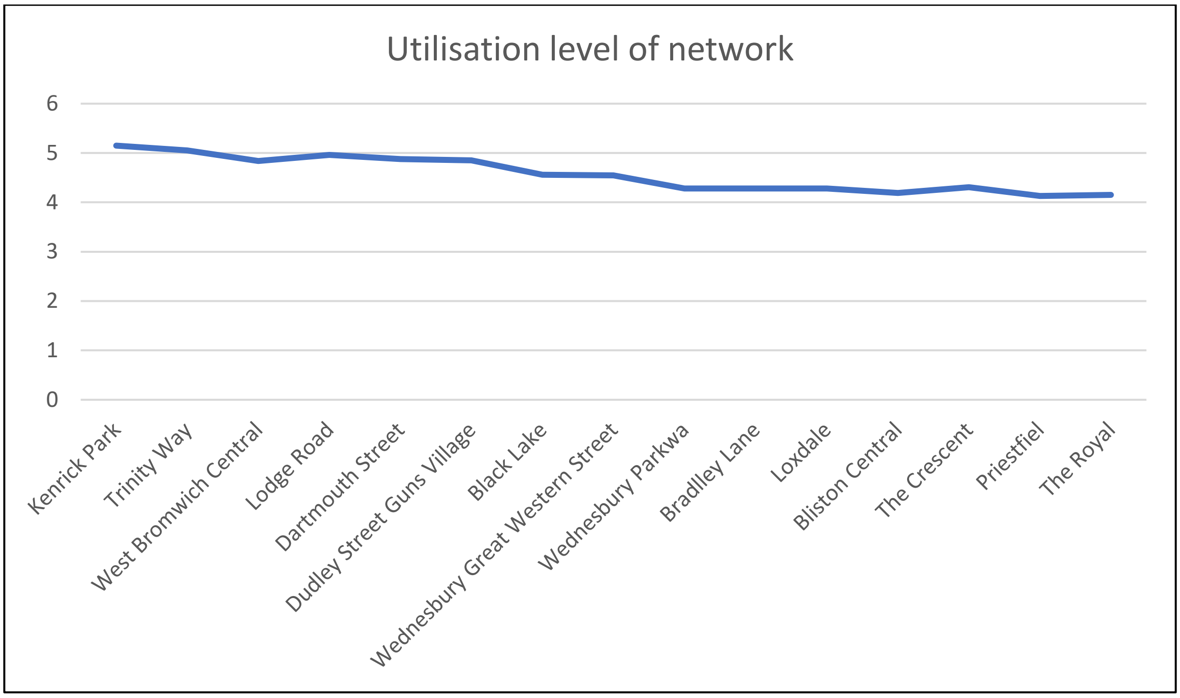

Figure 12 – Utilisation level of the network at each station

— Utilisation Levels: *Figures 11* and *12* provide insights into the utilisation levels of the metro network at each station. Utilisation levels reflect the degree to which resources are effectively leveraged to meet passenger demand. Analysis of these figures reveals varying utilisation patterns across stations, with some stations operating at near-maximum capacity while others exhibit underutilisation. Stations like Brindley Place and Town Hall demonstrate high utilisation levels, indicating efficient resource allocation and effective service provisioning. In contrast, other stations display lower utilisation levels, suggesting opportunities for optimising resource allocation and enhancing service efficiency.

The observed fluctuations in service counts and utilisation levels underscore the need for targeted interventions to optimise operational performance and enhance passenger satisfaction within the West Midlands Metro system. Spatial inconsistencies in service delivery highlight the importance of aligning resource allocation with passenger demand patterns across different stations. By identifying stations with low service levels and underutilised resources, metro operators can strategically reallocate resources, adjust service frequencies and implement targeted interventions to improve service consistency and efficiency.

Moreover, the findings underscore the systemic inefficiencies within the metro network, necessitating holistic approaches to enhance system-wide performance. By leveraging the insights gleaned from the simulation-based analysis, metro operators can develop data-driven strategies to address operational challenges, optimise resource utilisation and enhance the overall functionality of the metro system.

In summary, the results of the simulation-based analysis provide a comprehensive understanding of the operational dynamics of the West Midlands Metro system, laying the groundwork for evidence-based decision-making and targeted interventions to improve service quality, efficiency and passenger satisfaction.

4.2 Scenario 1: Increased service frequency

To explore the potential for increasing the utilisation levels of the West Midlands Metro, a new simulation model was developed to evaluate the impact of increasing service frequency. The current scenario involves a departure interval of 10 minutes. In this enhanced service scenario, an additional service is introduced, resulting in a metro departure every 5 minutes. This increased frequency aims to optimise resource utilisation across the network. *Table 5* presents the adjusted departure schedule for the West Midlands Metro under the enhanced service frequency scenario.

The intention behind this adjustment is to test the hypothesis that increased service frequency can lead to higher utilisation levels and better operational efficiency. By examining the outcomes of this revised schedule through simulation, we can gain insights into the potential benefits and challenges associated with more frequent metro services. The subsequent figures and analysis will delve into the impact of this new schedule on service completion rates and utilisation levels across the network.

Table 5 – Revised departure schedule with increased service frequency

	Minutes after midnight		**Minutes after midnight**
	315		545
Additional service	320	Additional service	550
	325		555
Additional service	330	Additional service	600
	335		605
Additional service	340	Additional service	610
	345		615
Additional service	350	Additional service	620
	355		625
Additional service	400	Additional service	630
	405		635
Additional service	410	Additional service	640
	415		645
Additional service	420	Additional service	650
	425		655
Additional service	430	Additional service	700
	435		705
Additional service	440	Additional service	710
	445		715
Additional service	450	Additional service	720
	455		725
Additional service	500	Additional service	730
	505		735
Additional service	510	Additional service	740
	515		745
Additional service	520	Additional service	750
	525		755
Additional service	530	Additional service	800
	535		805
Additional service	540		

The subsequent *Figures 13–16*, illustrate the impact of the enhanced service frequency on service completion rates and utilisation levels across the network.

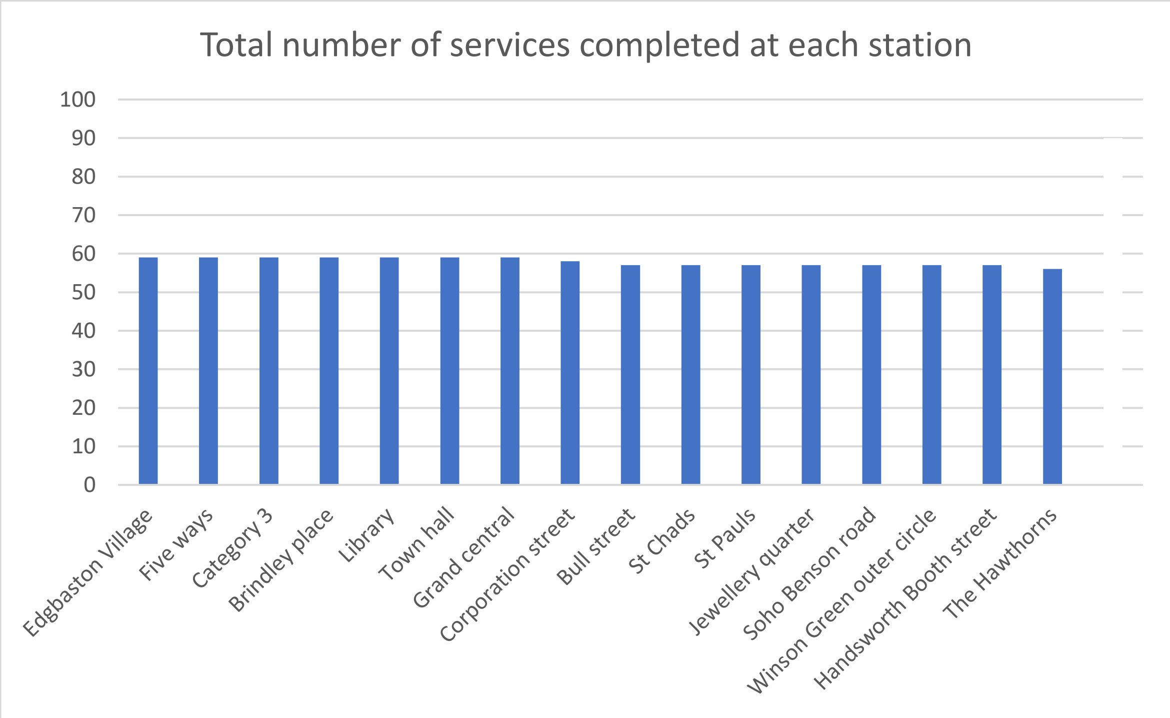

Figure 13 – Total number of services completed at each station with enhanced service frequency

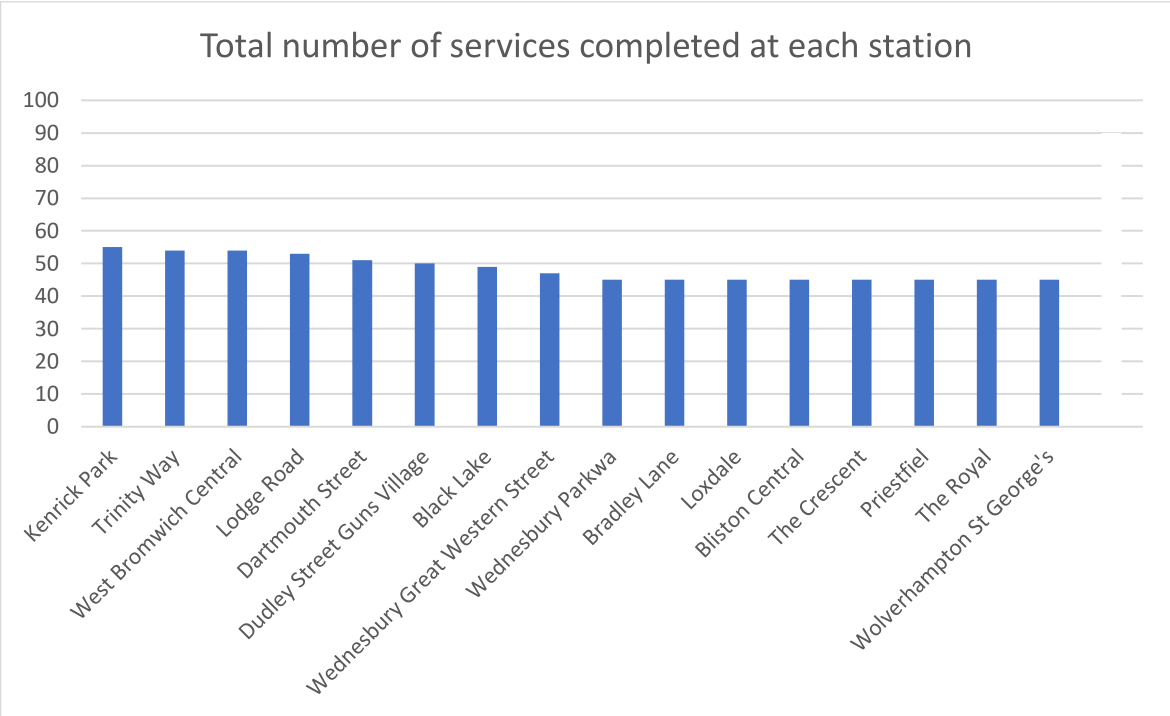

Figure 14 – Total number of services completed at each station with enhanced service frequency

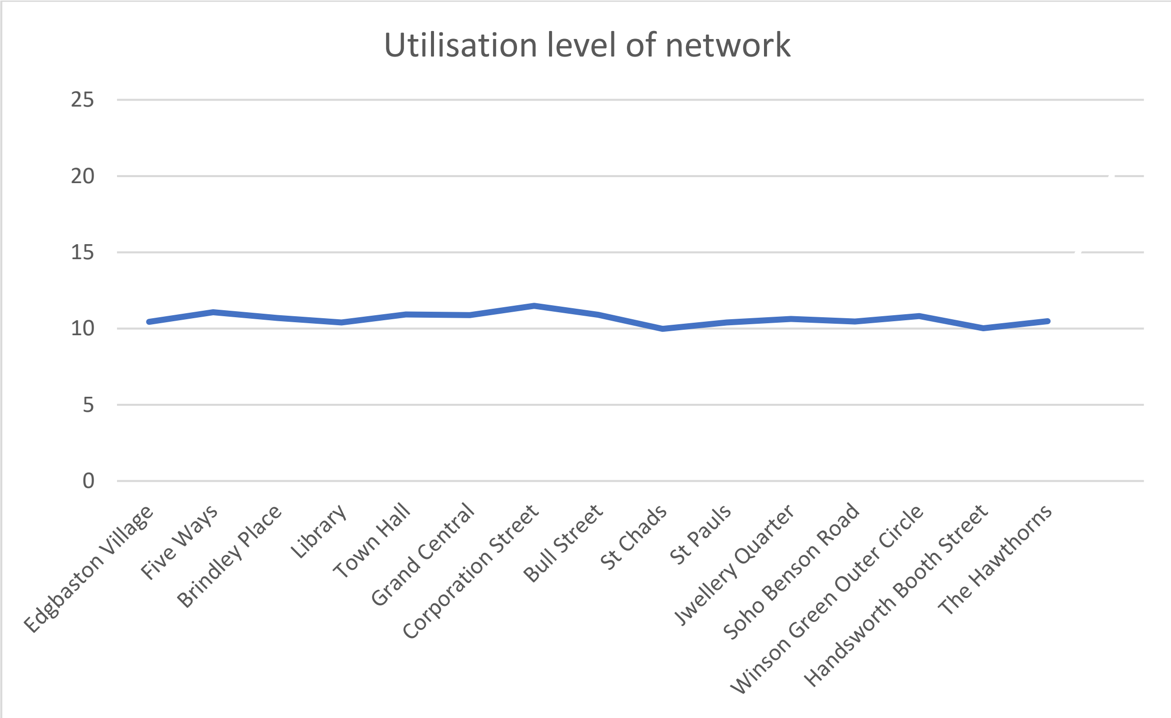

Figure 15 – Utilisation level of the network at each station with enhanced service frequency

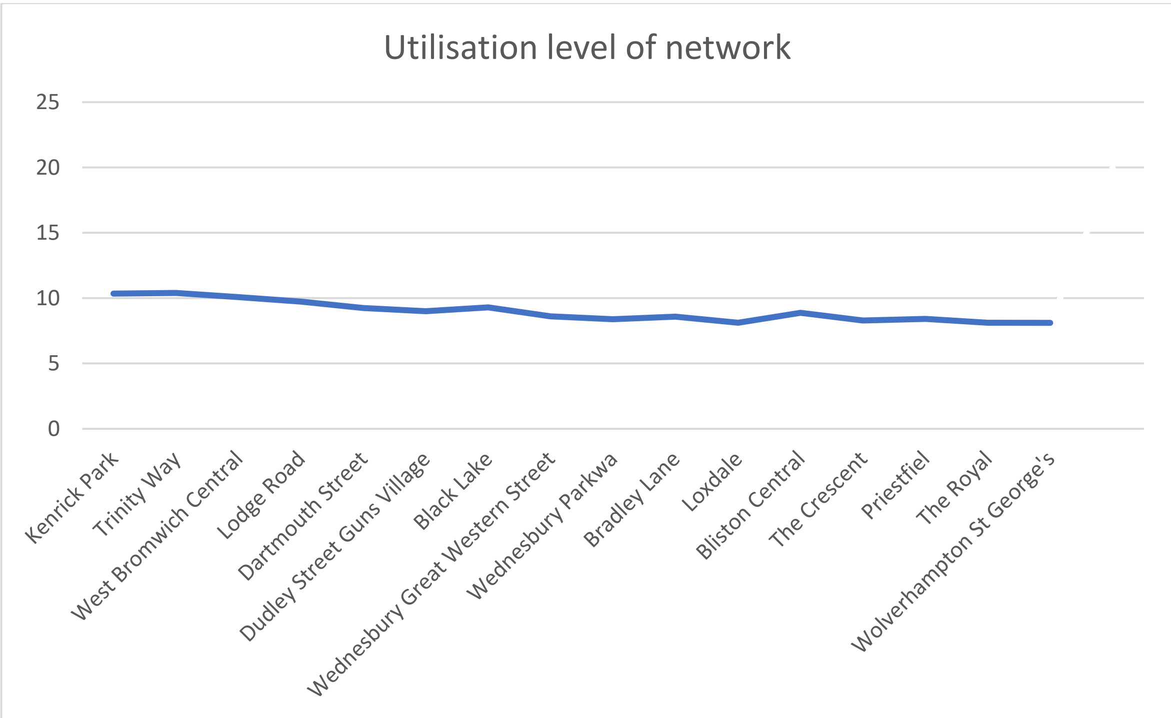

Figure 16 – Utilisation level of the network at each station with enhanced service frequency

The results from the simulation model indicate a significant increase in the total number of services completed at each station, suggesting that increasing the frequency of metros is an effective strategy. The utilisation levels also show marked improvements across the network, indicating a more efficient use of resources and better service provision for passengers.

4.3 Scenario 2: Introducing minor disruptions at major stops

While increasing the number of metro services is beneficial, it can also introduce several issues and concerns that need to be evaluated for a realistic understanding of the West Midland Metro system. Three major concerns include:

— Disruption in High Population Areas: Major stops such as Brindley Place, Grand Central, Corporation Street, Bull Street and St. Chads are highly populated, potentially leading to disruptions in the metro line passing through these areas.
— Risk of Delays: Increased service frequency can lead to higher risks of delays, especially at busy stations.
— Safety Issues: Major populated stops can also present safety issues due to large numbers of people crossing the tracks and inadequate infrastructure to prevent such crossings.

To address these potential issues while maintaining high utilisation, a new simulation model was developed by introducing minor disruptions at the major populated and popular stops. The distribution for each activity at these stops is set to "Exponential" instead of "Average" to simulate the variability and potential delays realistically.

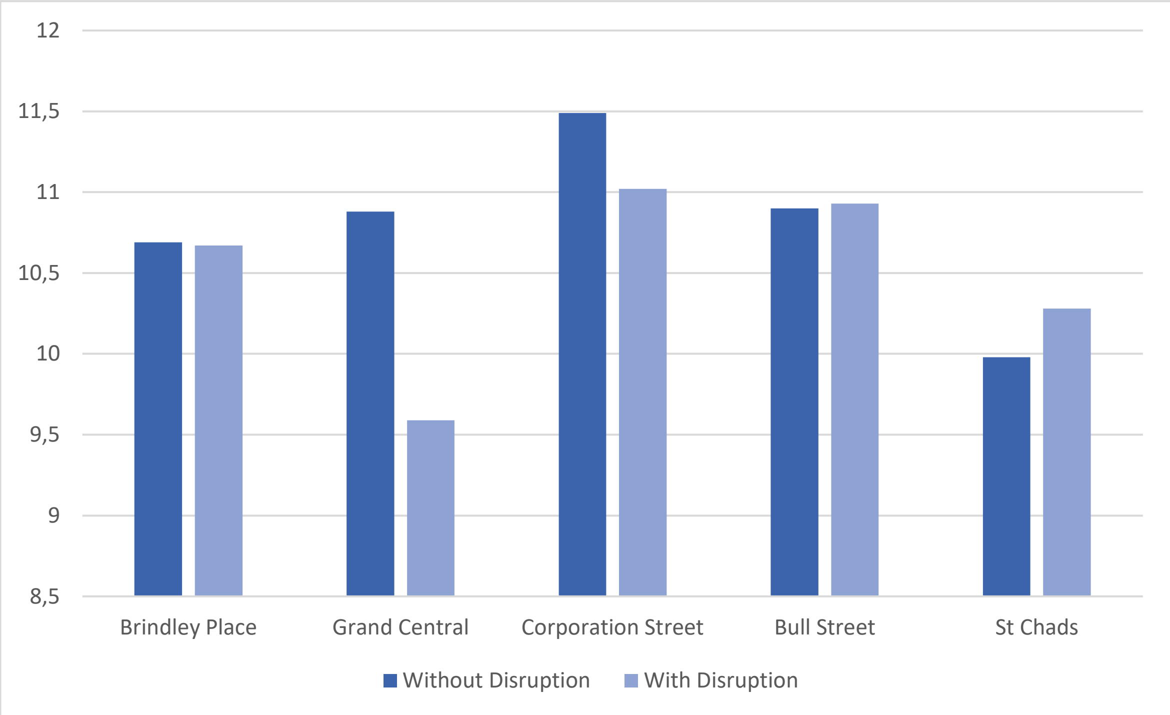

Figure 17 – Difference in utilisation level of the network at busy stations

The simulation results indicate that the total number of services completed at these stops remains largely unchanged despite the introduction of minor disruptions. There is only a small deflection in the utilisation levels, showing a slight reduction when disruptions are introduced (*Figure 17*). This realistic evaluation suggests that the West Midlands Metro system can maintain high service levels and utilisation rates even with potential minor disruptions, though some minor adjustments may be necessary to mitigate the impact caused.

5. CONCLUSION

The simulation-based evaluation of the West Midlands Metro system presented in this paper revealed crucial insights into its operational dynamics, highlighting both strengths and areas for improvement. The study employed the SIMUL8 software to model various scenarios, analysing service counts, utilisation levels and the impact of increased service frequencies and disruptions. The findings provided a comprehensive understanding of the metro system's performance, evaluating strategies for enhancement.

— The analysis of the current operational scenario (Scenario 0) showed fluctuating service counts and utilisation levels across different stations. Stations from Edgbaston to Grand Central exhibited relatively higher and uniform service counts, indicating robust operational performance. In contrast, stations from

The Hawthorns to Wolverhampton St. George's showed lower and fluctuating service counts, suggesting potential areas for improvement in service consistency and frequency.
- Utilisation levels varied significantly across the network. Stations like Brindley Place and Town Hall demonstrated high utilisation levels, indicating efficient resource allocation, while other stations displayed lower utilisation, pointing to opportunities for optimisation.
- Introducing additional services (Scenario 1), resulting in a departure every 5 minutes, significantly increased the total number of services completed at each station. This change led to improved utilisation levels across the network, demonstrating the effectiveness of increasing service frequency as a strategy to enhance operational efficiency.
- The enhanced frequency scenario illustrated that higher service frequencies could lead to more efficient use of resources and better service provision, ultimately improving passenger satisfaction.
- Introducing disruptions (Scenario 2) at major populated stops (Brindley Place, Grand Central, Corporation Street, Bull Street and St. Chads) to simulate potential delays and safety issues showed minimal impact on the total number of services completed. The slight reduction in utilisation levels indicated the network's resilience to disruptions. However, it is important to plan for disruptions to maintain high service levels and utilisation rates, highlighting the need for adaptive strategies to mitigate potential impacts.

To further enhance the operational efficiency and reliability of the West Midlands Metro system, the following avenues for future work are proposed:
- Implement adaptive scheduling using real-time data to dynamically adjust service frequencies based on passenger demand and operational conditions. This approach can optimise resource allocation and improve service reliability.
- Leverage AI and machine learning techniques to predict maintenance needs, optimise scheduling and manage disruptions more effectively. These technologies can enhance overall responsiveness, reducing downtime and improving service reliability.
- Invest in infrastructure improvements at major populated stops to mitigate safety risks and manage high passenger volumes. Enhanced safety measures, such as barriers and improved signage, can prevent track crossings and ensure passenger safety.
- Develop comprehensive resilience strategies to handle environmental disruptions and peak operation challenges. This includes implementing a three-stage PEL (prevention, response, learning) resilience framework to ensure robust metro operations under adverse conditions.

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प्रचिती शिंदे, मारिन मारिनोव

वेस्ट मिडलँड्स मेट्रोच्या ऑपरेटिंग सरावाचे मूल्यांकन करण्यासाठी इव्हेंट-आधारित सिम्युलेशन मॉडेलिंग

गोषवारा:
मेट्रो नेटवर्कचा झपाट्याने होणारा विस्तार, शहरीकरण आणि पर्यावरणीय शाश्वततेवर वाढलेले लक्ष, कार्यक्षम आणि शाश्वत सार्वजनिक वाहतूक व्यवस्थेची गरज अधोरेखित करते. या अभ्यासात वेस्ट मिडलँड्स मेट्रो सिस्टीमचा उपयोग ऑपरेशनल कार्यक्षमता आणि जागतिक स्तरावर मेट्रो नेटवर्कवर सामान्य असलेल्या वापरातील आव्हानांचा अभ्यास करण्यासाठी केस स्टडी म्हणून केला जातो. SIMUL8 सह प्रगत सिम्युलेशन मॉडेलिंगचा वापर करून, हे संशोधन वेस्ट मिडलँड्स मेट्रोच्या विद्यमान वेळापत्रकांचे आणि वापराच्या दरांचे मूल्यमापन करून अकार्यक्षमता आणि अप्रयुक्त क्षमता उघड करते. मेट्रो ऑपरेशन्स ऑप्टिमाइझ करण्यासाठी कृतीयोग्य अंतर्दृष्टी प्रदान करण्यासाठी वाढीव सेवा फ्रिक्वेन्सी आणि उच्च-रहदारी स्थानकांवर व्यत्यय यांसह विविध परिस्थितींचे अनुकरण केले गेले. प्रत्येक 10 मिनिटांवरून प्रत्येक 5 मिनिटांनी सेवा वारंवारता वाढवल्याने उपयोगाची पातळी वाढली आणि पूर्ण झालेल्या सेवांच्या एकूण संख्येत वाढ झाली. दरम्यान, प्रमुख थांब्यांमधील व्यत्ययांमुळे नगण्य श्रेणीतील वापर कमी झाला. हे परिणाम दर्शवितात की सुधारित सेवा वारंवारता ऑपरेशनल कार्यक्षमतेत लक्षणीयरीत्या वाढ करते आणि एकूण कार्यक्षमतेवर कमीतकमी प्रभावासह व्यत्ययांसाठी लवचिकता दर्शवते. भविष्यातील संशोधनाबाबत, अभ्यासात असे सुचवण्यात आले आहे की AI-चालित देखभाल आणि पायाभूत सुविधांच्या सुधारणांद्वारे अनुकूली वेळापत्रक लागू केल्याने मेट्रो ऑपरेशन्सची कार्यक्षमता आणि प्रवाशांचा अनुभव आणखी वाढू शकतो.

कीवर्ड:
मेट्रो प्रणाली मूल्यांकन; सिम्युलेशन मॉडेलिंग; वापर विश्लेषण; परिस्थिती