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REVIEW ARTICLE

The State-of-the-Art Development and New Challenges: Operations Management of Metro Systems

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Abstract

This paper comprehensively reviews literature on the operations management of metro systems, which are crucial for urban mass transit. It classifies the existing research into five categories: 1) passenger demand prediction; 2) timetabling and scheduling; 3) system vulnerability, resilience and performance; 4) resource planning; and 5) evacuation optimization. The paper focuses on publications in the last decade in order to reflect the latest research and industrial trends. In addition, some limitations of the existing literature are located and the potential knowledge gaps are identified. The paper provides a useful reference for developing sustainable and resilient metro systems to meet the needs of expanding cities while maintaining high standards of safety, reliability, and efficiency.

Keywords: metro systems, operations management, resource optimization, sustainable development.

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1 Introduction

As urban areas continue expanding, the reliance on efficient and reliable metro systems becomes increasingly important. Metro systems serve as the lifeblood of cities, facilitating the movement of millions of commuters daily and contributing to the overall sustainability and livability of urban environments. However, the complex and dynamic nature of metro systems presents numerous challenges in ensuring their smooth and uninterrupted operations [1].

The existing literature review papers in the field of metro operations management have provided valuable insights (see [2], for instance). Nevertheless, they often fall short in capturing the full range of issues and advancements. For instance, some review papers concentrate on individual aspects of metro systems, such as energy efficient operation [3], air quality [4], or disruption management [2], which offer non-comprehensive views of systems. Some other review papers may be a little outdated and fail to reflect the most recent works [28].

In response to these limitations, this paper presents a comprehensive literature review of the publications

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of the last decade, focusing on the critical aspects of metro operations management. It aims to capture the latest research and industry trends, ensuring that the findings reflect the state-of-art of the field and the emerging needs of urban transit.

In consistent with [31] and [2], the literature can be analyzed from five perspectives: strategic, tactical, systemic, operational, and emergency. As a result of that, the existing research can be classified into five categories: 1) passenger demand prediction; 2) timetabling and scheduling; 3) system vulnerability, resilience and performance; 4) resource planning; and 5) evacuation optimization. The correspondence between our division and different levels can be found in Table 1.

This paper will carefully examine each category to identify the contributions, methodologies, and the limitations. This approach allows for a comprehensive understanding of the complexities involved in maintaining a robust and resilient metro system.

This paper extends the current understanding of metro operations management by addressing the knowledge gaps and limitations identified in existing studies. The novelty and contributions are summarized as follows:

1. Unlike existing review papers that often focused on specific subsystems of a metro system, this paper takes a holistic approach to examining a metro system, which will allow for an in-depth understanding of the interactions and complexities involved in maintaining robust and resilient metro systems.
2. By concentrating on publications from the last decade, this paper captures the latest research findings and industry practices, which ensures that the insights provided are up-to-date and reflective of the current state of the field, as well as the emerging needs of urban transit.
3. The paper classifies the existing works into five categories: 1) passenger demand prediction; 2) timetabling and scheduling; 3) system vulnerability, resilience, and performance; 4) resource planning; and 5) evacuation optimization. This structured approach allows for a thorough examination of each category, identifying prevalent methodologies, key findings, and the extent of their contributions to the field.
4. The paper offers practical recommendations for future research to address identified limitations and enhance knowledge in metro operations management, which provides a useful reference for researchers, offers practical advice for metro operators and policymakers, and contributes to the performance and resilience management of metro systems and the development of sustainable urban transit.

The remainder of this paper is structured as follows. Section 2 reviews existing works. Section 3 identifies knowledge gaps. Section 4 concludes the paper.

2 Related Work

A detailed literature classification is shown in Figure 1. The structured categorization of the literature review for metro system operations management follows a logical sequence that is consistent with the operational life-cycle of a metro system. It begins with **Passenger Demand Prediction**, which serves as the basis for all subsequent planning and operational decisions. Understanding the volume, patterns, and dynamics of passenger flow enables the development of strategies that cater to the needs of the commuting public.

Timetabling and Scheduling become the next critical step, where the insights from demand prediction are translated into actionable plans that allocate the movement of trains. This step improves the probability that a metro system can accommodate the projected demand while maintaining punctuality and efficiency.

Subsequently, **System Vulnerability, Resilience and Performance** considerations come into play, focusing

Table 1. Correspondence between research components and operational levels.

Component	Level	Focus
Passenger Demand Prediction	Strategic	Anticipating future needs
Timetabling and Scheduling	Tactical	Coordinating service delivery
System Vulnerability & Resilience	Systemic	Ensuring robustness and adaptability
Resource Planning	Operational	Efficient utilization of resources
Evacuation Optimization	Emergency	Minimizing harm during disruption

on the consistent delivery of high-quality services and the robustness of a metro system against various operational challenges. This encompasses the reliability of service delivery, the resilience of the system to disruptions, and the overall performance metrics that reflect the effectiveness of the system.

In the realm of **Resource Planning**, there is a strategic focus on the allocation and management of resources to prepare for and mitigate potential operational disruptions. This involves a meticulous approach to ensuring that the metro system has the necessary resources in place to respond effectively to various challenges, thereby enhancing its resilience and operational readiness.

Evacuation Optimization is a key consideration for safeguarding passengers and staff. It involves the development and refinement of evacuation processes, ensuring that in the event of an emergency, the metro system can facilitate a swift, orderly, and safe evacuation. The optimization of these procedures is crucial for minimizing risks and maximizing the efficiency of response efforts, contributing to the overall robustness of the metro system.

The above categorization captures the essence of managing a metro system's operational complexities, ensuring safety, efficiency, and reliability in service delivery.

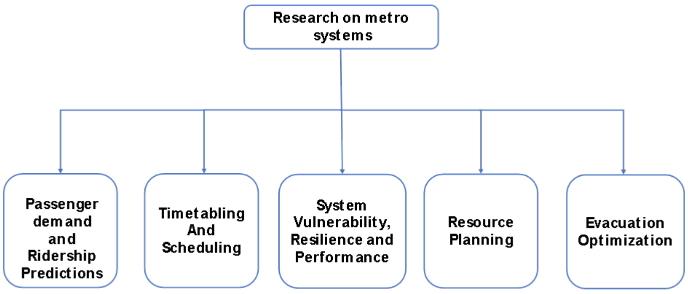

Figure 1. A taxonomy of the existing research on metro systems.

Using CiteSpace, we analyzed publications in the relevant fields over the past five years. To define the scope of the relevant literature, we conducted keyword-based searches on Web of Science using the five category labels, and limited the results to research-type articles. The clustering results and time-based trends from the literature analysis are presented in Figures 2 and 3, respectively. Specifically, Figure 2 shows the results of a clustering analysis, highlighting the key keywords in the metro system domain. The most central clusters include transportation and society, time-dependent demand, optimization, emergency evacuation, and patterns. Figure 3 illustrates the temporal evolution of keywords and methodological trends from 2020 to 2025. Around 2020, the focus of research was mainly on assignment, algorithm, and optimization. As time progressed, the emphasis gradually shifted toward more complex scenarios such as dynamics, environment, and timetabling.

The following subsections will review each category.

2.1 Literature on passenger demand and ridership predictions

Research in recent years has significantly advanced our understanding of metro systems, particularly in the areas of passenger demand and ridership predictions. [66] made an excellent contribution by introducing a novel approach for forecasting ridership in urban transit systems using network Kriging, specifically applied to the Second Avenue Subway in New York City. Their study, however, was limited in its applicability to other systems with varying network structures and demand patterns, as it did not account for the potential impact of real-time data on ridership estimation. [25] conducted a study in Chongqing, China, to investigate the linkage between passenger demand and surrounding land-use patterns at urban rail transit stations, providing spatial distribution insights through canonical correlation analysis. The study's reliance on cross-sectional data, however, may have obscured the temporal dynamics of passenger demand and land-use changes. [39] furthered this discussion by exploring the determinants of rail transit passenger volume and its implications for transit-oriented development planning. Their study enhanced the understanding of usage factors but fell short in accounting for the potential influence of service quality or individual preferences on passenger volume. [22] integrated an optimized multivariate mode decomposition strategy and long short-term memory model to estimate passenger flow intervals, combining deep learning and ensemble learning advantages. However, the effectiveness of the model in low-data scenarios remains to be tested. [10] proposed a neural network model to predict short-term metro passenger flow, leveraging spatial and temporal features extracted from historical data. However, the model's reliance on historical data may not fully capture the unpredictability of real-time demand. [55] combined domain knowledge of transportation with deep learning to predict network-level metro passenger flow, capturing spatial-temporal evolution.

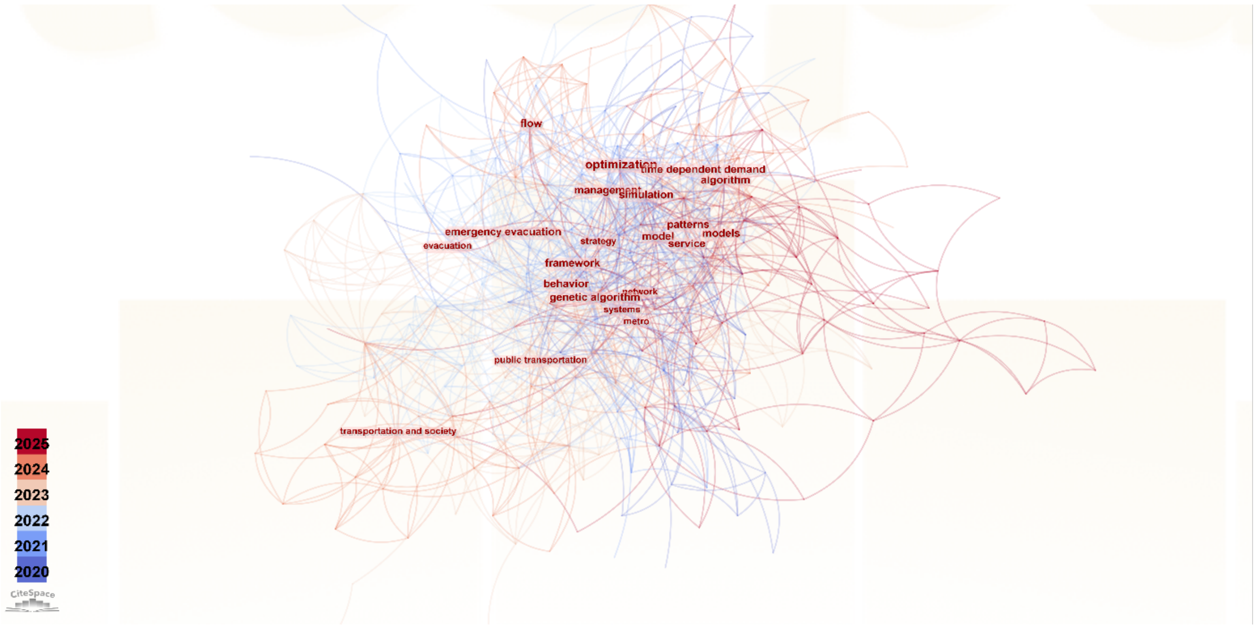

Figure 2. Keywords and research domains (CiteSpace).

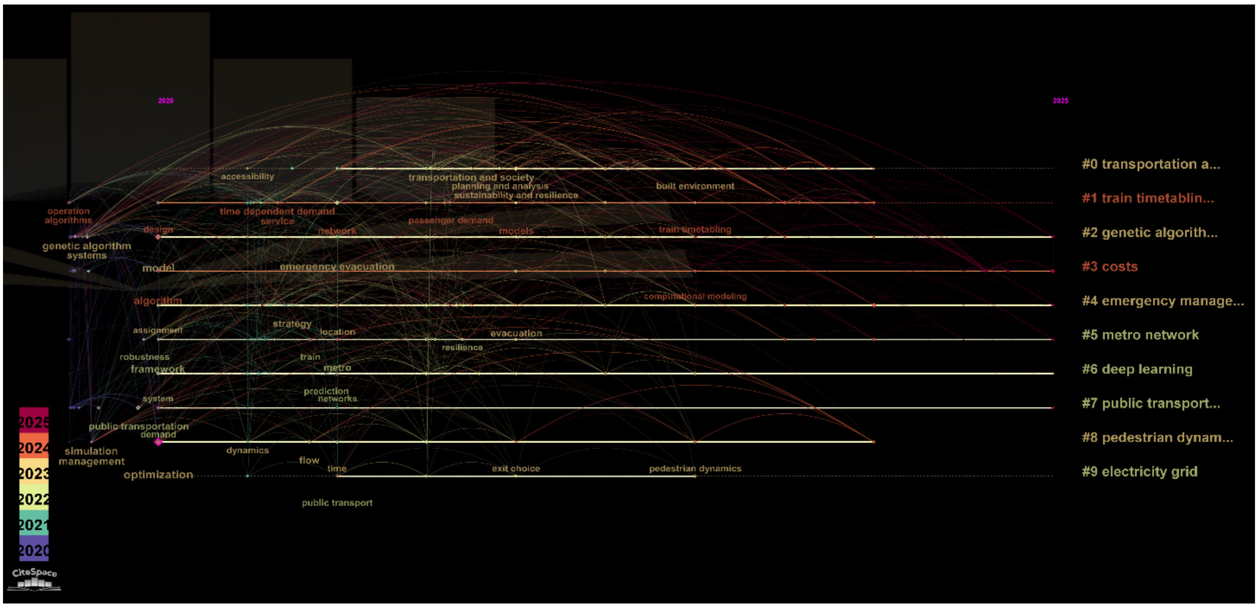

Figure 3. Evolution of research topic and methodology (CiteSpace).

The model's complex architecture demands substantial computational resources and may underperform in areas with sparse or inconsistent data.

The authors considered that the impact of weather conditions and extreme events on metro ridership and the development of models for travel demand had been a key area of exploration. [23] conducted a study in Nanjing, China, to assess the fluctuation in ridership under various weather conditions, emphasizing the significant influence of weather on the number of passengers. The study, however, did not consider the potential confounding effects of other factors such as holidays or special events. [17] modeled the determinants of travel demand between rail stations in the Washington D.C. Metrorail system using multilevel analysis, providing a detailed look at inter-station travel demand factors. The study's focus on a single system may limit the extrapolation of its findings to other urban areas with diverse demographic and spatial characteristics. Additionally, [34] introduced a geographically and temporally weighted regression model to explore the spatiotemporal influence of the built environment on transit ridership, enhancing understanding of urban development impacts but potentially limited by the data's spatial and temporal resolution. [24] examined the potential effect of a

100-year pluvial flood event on metro accessibility and ridership in central Shanghai, highlighting vulnerabilities within the system. The case study emphasized the need to consider such events in urban planning and infrastructure development although the findings may have limitations when applied to regions with different flood risks and infrastructure.

In summary, these studies have enriched our understanding of metro systems by examining various aspects such as ridership estimation, the impact of weather conditions, and the implications of extreme weather events. A taxonomy is shown in Figure 4, which categorizes the different methodologies and approaches used across the studies.

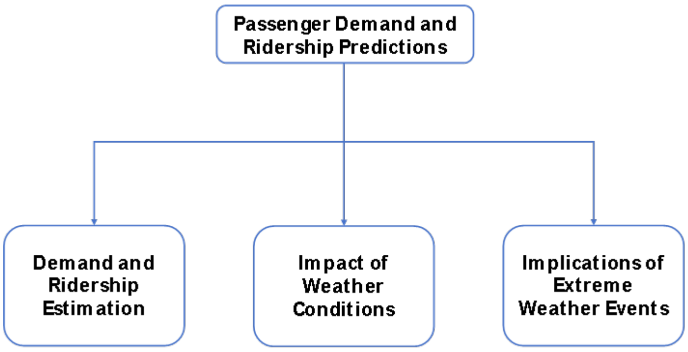

Figure 4. A taxonomy on the existing research on passenger demand and ridership predictions.

However, each study has its limitations. Specifically, in the area of passenger demand and ridership predictions, many models rely heavily on historical data, which may not always accurately capture future trends, especially in the context of rapidly changing urban environments or unprecedented events like pandemics. Additionally, these models often assume a static relationship between variables such as weather or public holidays and ridership, which may overlook more dynamic or complex patterns that emerge in real-world conditions.

Furthermore, a key limitation in many studies is the insufficient consideration of social, economic, and behavioral factors that influence passenger demand. For example, demographic shifts, socioeconomic status, and changes in consumer behavior due to emerging technologies like ride-hailing or shared mobility services may not be fully incorporated into predictive models. These factors can significantly alter ridership patterns in ways that current models fail to anticipate. Further research is imperative to address these limitations and to continue broadening our knowledge in this field.

2.2 Literature on Timetabling and Scheduling

The development of robust optimization approaches for metro timetabling has been a key area of focus. [75] introduced a robust method that prioritizes reducing passenger wait times, a critical aspect of service quality. However, its widespread adoption may be hindered by the need for precise data on passenger flow and system behavior. [64] proposed a comprehensive optimization model that integrates train timetables, rolling stock assignment, and short-turning strategies, aiming to enhance both efficiency and service quality. However, the complexity of the model and the data requirements may pose challenges for its practical application. [16] developed a computationally efficient method that incorporates uncertain transfer walking times into metro train timetables, improving network-wide efficiency. This method addresses the variability of transfer times but requires restrictive assumptions regarding passenger behavior and walking times.

Further studies have refined approaches for metro timetabling and scheduling, with a focus on human intervention and network integration. [44] examined the role of human intervention in timetable rationalization, suggesting that human decision-making can lead to more efficient and adaptable schedules. However, the effectiveness of incorporating human judgment may vary and could be limited by the unpredictability of human factors. [3] proposed a model for commuter-metro networks, focusing on the integration of commuter lines with metro lines to facilitate seamless passenger transfers. This work addresses the complexity of multi-line transit networks but may face challenges in implementation due to the need for coordination between different transit authorities. [76] presented a demand-driven approach that integrates train timetabling with rolling stock scheduling, addressing the dynamic nature of passenger demand. However, the adaptability of this approach may be limited by the requirement on the accuracy of demand forecasting and the responsiveness of the system to real-time changes.

[6] utilized complex network theory to measure the importance of different lines and directions at transfer stations, contributing to the development of a multi-period optimization model for metro timetabling. While this approach creates novelty, its practical applicability may be limited by the restrictive assumptions made regarding passenger demand and the complexity of the model. [45]

tackled safety challenges in metro train timetabling, particularly on congested lines, ensuring safety while adapting to passenger flow changes. However, the model's effectiveness may be limited by its unrealistic assumptions about demand elasticity and the predictability of crowd patterns.

[52] addressed the importance of rescheduling operations during the last train period, aiming to balance service quality with operational costs. This approach is crucial for off-peak efficiency but may face limitations in handling unpredictable variations in passenger load. [65] employed a decomposition and approximate dynamic programming method to optimize metro train timetables and skip-stop plans, enhancing network efficiency. The practical application might be constrained by the complexity of the approach and the need for data of high quality. [71] introduced a rescheduling method to minimize the capacity loss due to line disruptions, constrained by system reliability. This approach is vital for maintaining operational stability but may have limitations in real-time adaptability to unforeseen disruptions. [46] developed a hybrid approach combining deep reinforcement learning and adaptive large neighborhood search for integrated train and rolling stock rescheduling, enhancing operational resilience. Their method, while innovative, may require significant computational resources and extensive training data.

The latest research in metro timetabling includes advancements in scheduling and multi-modal integration. [26] presented a bi-directional transfer model for synchronizing metro and high-speed train schedules during late-night operations, improving inter-modal connectivity. However, this model may face challenges in coordinating schedules across different transportation authorities. [11] explored the integration of metro trains and shuttle buses, contributing to multi-modal transportation understanding. However, the complexity of managing such integration may hinder its practical applications. [72] proposed an approximate dynamic programming method for efficient timetabling with stop-skipping, aiming to balance efficiency and passenger experience.

A taxonomy is shown in Figure 5, which outlines the various approaches used to optimize metro operations, including timetabling, scheduling, and the management of passenger flow.

However, despite these advancements, *Timetabling and Scheduling* models often face significant limitations.

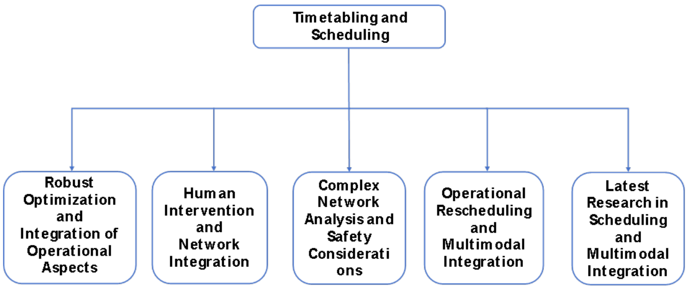

Figure 5. A taxonomy on the existing research on timetabling and scheduling.

One key challenge is the dynamic nature of passenger demand, which can fluctuate rapidly due to factors such as peak travel times, weather conditions, and unexpected events (e.g., service disruptions or accidents). Current models typically rely on fixed schedules or assumptions of predictable demand, which may not accurately reflect the real-time variability of ridership. This can lead to inefficiencies such as overcrowded trains during peak hours or underutilized services during off-peak periods.

Moreover, many scheduling models struggle with multi-objective optimization, where conflicting objectives such as minimizing waiting time, reducing operational costs, and optimizing train capacity need to be balanced. The complexity of these trade-offs is often difficult to capture in traditional models, which tend to prioritize one objective at the expense of others. For example, focusing primarily on reducing travel time may inadvertently lead to overcrowding during peak hours, whereas focusing on increasing frequency could drive up operational costs.

2.3 Literature of metro system vulnerability, resilience and performance

In the study of metro system vulnerability, resilience and performance, understanding passenger route choice behavior is crucial for improving system efficiency and passenger experience. [42] conducted a behavioral comparison of route choice on metro networks, considering factors such as time, transfers, crowding, topology, and socio-demographics. The study revealed the complexity of passengers' route choice behavior and the influence of multiple factors. [73] developed a constrained multinomial Probit route choice model tailored for passengers in large-scale metro networks in China, offering new perspectives in route selection. The model's complexity, however, may limit its practical application in real-time operations. [49] examined the relationship between metro passenger behaviors and their involvement in metro incidents, identifying several passenger behaviors associated with a higher risk of incident involvement. [59] used a data-driven approach to unraveling traveler mobility patterns and predicting user behavior in the Shenzhen metro system, providing valuable insights for personalized services and proactive management strategies. [1] studied travel backward behavior in congested metros using a data-driven approach, providing insights into traveler behavior and how it might affect passenger flow.

Traveler satisfaction and the service reliability are key factors in maintaining and improving the usage of metro systems. [56] examined the factors affecting public transportation services, utilizing stop-level data from the Los Angeles Metro bus system. [62] studied traveler satisfaction in the Istanbul metro system, identifying the factors that influence satisfaction and emphasizing the importance of considering both objective measures of service quality and travelers' subjective perceptions. [36] proposed a data mining approach to predicting delayed trips, incomplete trips, and canceled trips in metro systems, providing insights into trip prediction and its potential impact on passenger behavior and satisfaction. [41] studied service quality measures adopted by Chennai metro rail operations during the pandemic, providing insights into maintaining passenger flow amidst challenging conditions. However, the findings may not be directly applicable to post-pandemic operations or other urban environments with different public health contexts.

The vulnerability of urban metro systems to disruptions and their environmental impact is an important consideration for sustainable and resilient urban transportation. [53] introduced a new node centrality measure for evaluating the level of utilization of stations and analyzed the robustness of a metro network under attack scenarios. [67] analyzed the networked characteristics of Beijing, Shanghai, and Guangzhou metro systems and investigated their vulnerability to malicious attacks. [28] reviewed traction drive system reliability evaluation, providing an overview of the methods and techniques used. [63] analyzed the perceived risk of public transportation users in Metro Manila during a flood event, providing insights into the factors influencing perceived risk. [33] reviewed risk assessment approaches for inundation of metro systems and proposed an approach for evaluating inundation risk. [54] proposed a tolerability index to measure the vulnerability of urban metro systems, taking into account factors such as satisfied route and shortest path. [68] proposed to abstract the topological structure of urban rail transit systems and applied moving block technology to calculate transportation functionality. [7] studied the impact of outdoor track segments and weather conditions on service interruptions and delays in metro systems. [8] proposed an approach to evaluating the criticality of different nodes in metro networks, considering centrality measures and entropy, which is related to passenger flow and node importance in network performance. [50] studied actual fatigue damage and operation data of Metro Bogie Frame, investigating the influencing factors. [18] developed a route redundancy based method to identify critical stations in metro systems. The study provided a new perspective on critical station identification but did not consider the potential impact of disruptions on passenger flow. [5] integrated system dynamics and Monte Carlo simulation to evaluate the vulnerability of the metro system in operation from a long-term perspective. [47] focused on the resilience of metro stations in case of fire, proposing fire resilience indices and using a Bayesian network to assess resilience. [69] proposed a method to detect metro service interruptions using Gaussian mixture models. [20] proposed a measure to assess the criticality of metro stations based on substitute complex network analysis. [30] used pair copula constructions and Bayesian networks to study the safety of metro tunnels, considering dependent influencing factors. [58] established an environmental assessment system for urban underground systems using a partial-least-square structural equation model. [15] used evidential reasoning for flood risk assessment and mitigation of metro stations, identifying critical factors and studying risk mitigation measures. The study's focus on the worst-case scenario, but the subjective assumptions made regarding parameters may limit the accuracy of the risk assessment.

In addition, with the development of information technology, many studies have begun to explore the impact of introducing new technologies on metro systems. [14] examine the use of information communication technologies in smart cities to improve citizens' lives and local economies, while addressing privacy and security concerns, identifying recent cyberattacks, and offering recommendations for future security improvements. [43] explored the concept of smart cities, focusing on cybersecurity issues and proposing a hybrid smart city cyber security architecture to address data protection and risks. [9] discussed the growing importance of smart trains and railways in solving traffic and environmental problems, highlighting the cybersecurity challenges and the need for stronger privacy and security measures to prevent cyberattacks.

In the streams of 5G technology, [12] discussed how 5G technology will impact intelligent transporting systems in smart cities, focusing on the technological context, economic benefits, and the implications for key industries such as energy, healthcare, and public transport. [51] evaluated the performance of current 5G deployments in supporting smart city applications through a pilot smart city project, revealing that while 5G can handle mobile video streaming, it struggles with data-intensive applications requiring real-time responsiveness.

In the streams of digital twins, [35] addressed challenges such as expensive infrastructure and limited signal reach, with an emphasis on the integration of real-time digital twins. [38] examined the adoption of machine learning-augmented digital twin systems in high-speed rail networks, highlighting their potential for predictive maintenance.

These studies collectively contribute to a deeper understanding of urban metro systems, their users, and the environmental and operational challenges they face. A taxonomy is shown in Figure 6, categorizing the various research areas and methodologies used to assess metro system vulnerability, resilience, and performance.

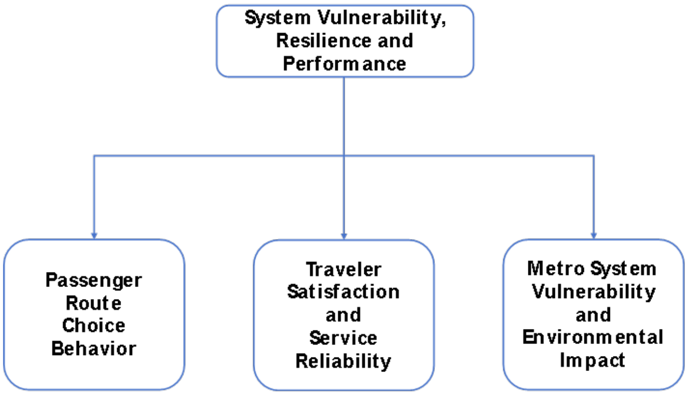

Figure 6. A taxonomy on the existing research on metro system reliability and performance.

However, each area of research has some limitations when applying to other contexts and systems. For example, studies on metro system vulnerability often focus on identifying potential risks such as infrastructure failure, extreme weather events, or security threats. While these studies help pinpoint weak points in the system, they may not fully account for the complex, interdependent nature of urban metro systems, where a failure in one subsystem can trigger cascading effects across the entire network. This complexity makes it difficult to model all potential vulnerabilities accurately, and often, the results are based on static risk assessments that fail to adapt to evolving conditions or new threats.

Similarly, research on resilience in metro systems typically explores how quickly a system can recover from disruptions. However, the metrics of resilience often focus on recovery times or the ability to maintain minimal service during crises, without fully addressing the broader trade-offs between resilience and efficiency. For instance, enhancing system resilience might require additional investments in redundant infrastructure or backup power, which can increase operational costs. Moreover, resilience models may not always consider the social and economic impacts of disruptions, such as passenger inconvenience, economic losses, or environmental damage, which are important for comprehensive resilience assessments.

In terms of system performance, many studies emphasize the importance of optimizing efficiency, such as reducing travel time, increasing capacity, and minimizing operational costs. However, performance measures often fail to fully capture passenger experience or service reliability, which are critical aspects of metro system performance. Factors such as train frequency, accessibility, and comfort can significantly affect user satisfaction but are not always adequately integrated into performance models. Additionally, metro systems in different cities or regions often face unique challenges, such as urban density, climate conditions, and financial constraints, which require tailored approaches to performance optimization.

2.4 Literature on resource planning

The field of resource planning within metro systems has witnessed remarkable progress, with a substantial emphasis placed on the management and optimization of passenger flow. [57] developed an algorithm for capacity-oriented passenger flow control in urban rail transit systems under uncertain demand. However, the study's reliance on a single case study may limit the extrapolation of the findings to other systems with different demand patterns and infrastructure. [37] optimized the alignment corridor of a new metro line by considering network vulnerability and assessing performance under disruption scenarios. The study accounted for new ridership and construction costs, but the quantitative approach may not fully capture the complexities of real-world disruptions and their impact on network performance. [27] aimed to reduce passenger waiting time by controlling passenger flow in origination-destination pairs, formulating the problem as a stochastic dynamic programming problem. However, the complexities of real-world passenger behavior may pose challenges in the practical implementation of the proposed solutions. [32] jointly optimized the robust passenger flow control strategy and train timetable on a congested metro line, trading off efficiency and service fairness. However, the effectiveness of the proposed solutions in dynamic and unpredictable real-world conditions may be limited. [40] concentrated on passenger flow uncertainties and delays, proposing a modular transit system and optimizing the metro system using a nonlinear programming model. However, the practical feasibility of implementing such a system and the assumptions made regarding passenger demand and operational constraints need further validation.

Energy optimization has also been key areas of research in urban metro systems. [61] optimized departure and arrival times of metro stations using a multi-objective model considering energy consumption, waiting time, and robustness. The study's multi-objective approach provided a comprehensive view of operational efficiency, but the model's complexity may pose challenges in practical implementation. [21] presented a train timetable rescheduling model to optimize energy consumption in metro systems, integrating genetic algorithms and long short-term memory based recurrent neural networks. However, the computational intensity of the model may limit its scalability for large-scale systems. [19] introduced a streamlined deterministic method for assessing the energy performance of underground metro stations, utilizing Monte Carlo simulations to enhance design robustness. However, the simplifications made in the deterministic model may not adequately account for the intricacies of actual energy consumption patterns.

In summary, these studies have significantly contributed to our understanding of urban metro systems, offering innovative approaches to passenger flow control and energy consumption optimization. A taxonomy is shown in Figure 7, which categorizes the various approaches and techniques used in resource planning within metro systems, focusing on optimizing the use of available resources such as trains, stations, energy, and personnel.

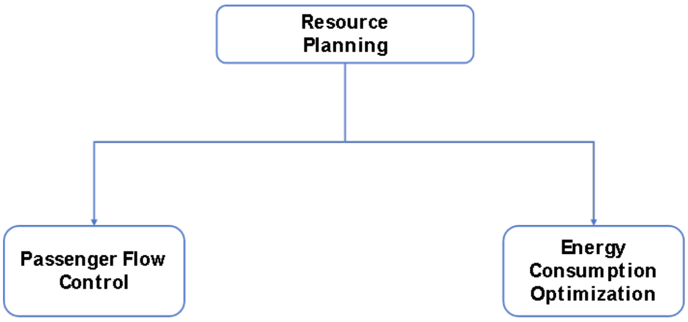

Figure 7. A taxonomy on the existing research on resource planning.

Current research on resource planning also has its limitations. In the area of resource planning, many existing models rely on assumptions of constant demand and fixed resource allocation, which do not fully account for the dynamic nature of urban metro systems. For example, variations in ridership patterns due to weather conditions, special events, or emergencies can lead to underutilization or overburdening of resources. While some models attempt to integrate flexibility in resource allocation, they often fail to fully capture real-time variability in passenger demand and service requirements. This can result in inefficiencies such as under-served stations during peak hours or excessive energy consumption due to overcapacity during off-peak periods.

Furthermore, energy consumption optimization is another area where limitations arise. Many studies focus on minimizing energy use through techniques such as energy recovery systems or optimizing train acceleration and deceleration. However, these models typically do not consider the full life-cycle costs of implementing energy-saving technologies, including the upfront infrastructure investments, maintenance, and the long-term impacts of different energy sources. Additionally, environmental factors, such as the energy demands of different weather conditions or varying passenger densities, are often underrepresented in optimization models, leading to suboptimal solutions in real-world applications.

In terms of personnel and asset management, studies often focus on optimizing schedules, maintenance, and staffing, but these models can overlook the human element of resource planning. For example, factors such as worker fatigue, skill diversity, and labor shortages can affect the system's overall performance but are not always integrated into resource planning frameworks. Moreover, the integration of new technologies, such as automated trains and smart scheduling systems, requires careful planning to ensure smooth transitions without disrupting service quality or efficiency. Further research is needed to address these limitations and to continue advancing our knowledge in this field.

2.5 Literature on evacuation optimization

Disruption management and pandemic operations are critical aspects of urban metro system research. [70] conducted a systematic review on metro system disruption management, outlining internal and external strategies. [48] used simulation-optimization to study traffic disturbance discovery in metro systems, combining a metro traffic simulator and an optimization solver. However, the effectiveness of the proposed solutions in dynamic and unpredictable real-world conditions may be limited. [74] studied the use of bridge buses to maintain service levels during metro disruptions, considering passenger experience, reliability, and capacity utilization. However, the effectiveness of the proposed solutions in diverse urban environments with varying infrastructure and passenger profiles needs further validation.

Moving beyond disruption management, the focus shifts to evacuation response and evacuation. [13] proposed a simulation-based approach for automatic evacuation evaluation and adaptive optimization at metro stations. However, the reliance on simulation data may limit the accuracy of real-world evacuation scenarios. [29] used simulation to study fire emergency response optimization in metro stations, employing hierarchical timed color petri nets and the skyline operator for multi-objective problem-solving. The study's simulation approach, but the practical implementation of the proposed solutions may be challenging due to the complexities of real-world emergency scenarios.

In summary, these studies have significantly contributed to our understanding of urban metro systems, offering innovative approaches to disruption management, and emergency response and evacuation. A taxonomy is as shown in Figure 8.

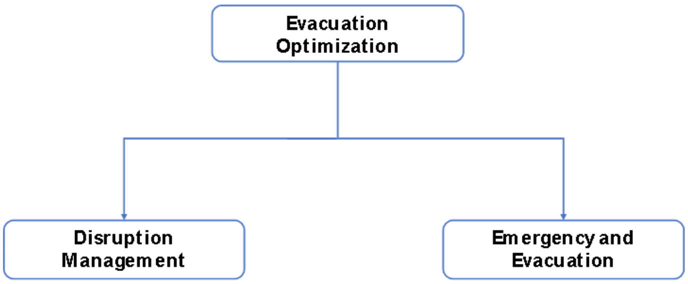

Figure 8. A taxonomy on the existing research on resource planning and evacuation optimization.

Research on evacuation optimization often simplifies key aspects such as passenger behavior, information availability, and infrastructure constraints. Many models assume rational and coordinated responses among passengers, neglecting panic, non-compliance, and limited awareness in real emergencies. In addition, the dynamic nature of disruptions—such as changing hazard zones, communication delays, or cascading failures—is rarely captured in full. These simplifications can limit the practical relevance of the findings when applied to large-scale or unexpected events. Moreover, few studies integrate real-time data or consider multimodal evacuation strategies, which are essential for adaptive and resilient emergency response planning. Further research is needed to address these limitations and to continue advancing our knowledge in this field.

3 Research Gap

This section aims to identify research gaps, which is summarized as in Figure 9.

3.1 Passenger Demand and Ridership Prediction

Future research in passenger demand and ridership prediction for metro systems should prioritize overcoming the limitations of current models and advancing our comprehension of these intricate systems. Efforts should be directed towards creating models with broader applicability across various metro systems, irrespective of their network structures, demand patterns, and geographical settings. This necessitates testing the applicability of existing models in diverse urban contexts to ascertain their extrapolation Furthermore, there is an urgent need for research that incorporates real-time data streams, such as passenger counts, traffic conditions, and service disruptions, into ridership prediction models. Doing so can capture the dynamic fluctuations in passenger demand and enhance the precision of forecasts. A deeper understanding of how service disruptions, including delays, equipment failures, and extreme weather events, influence ridership patterns and reliability is also imperative. Moreover, studies should emphasize the incorporation of the temporal dynamics of passenger demand and land-use changes into their analyses. This can be

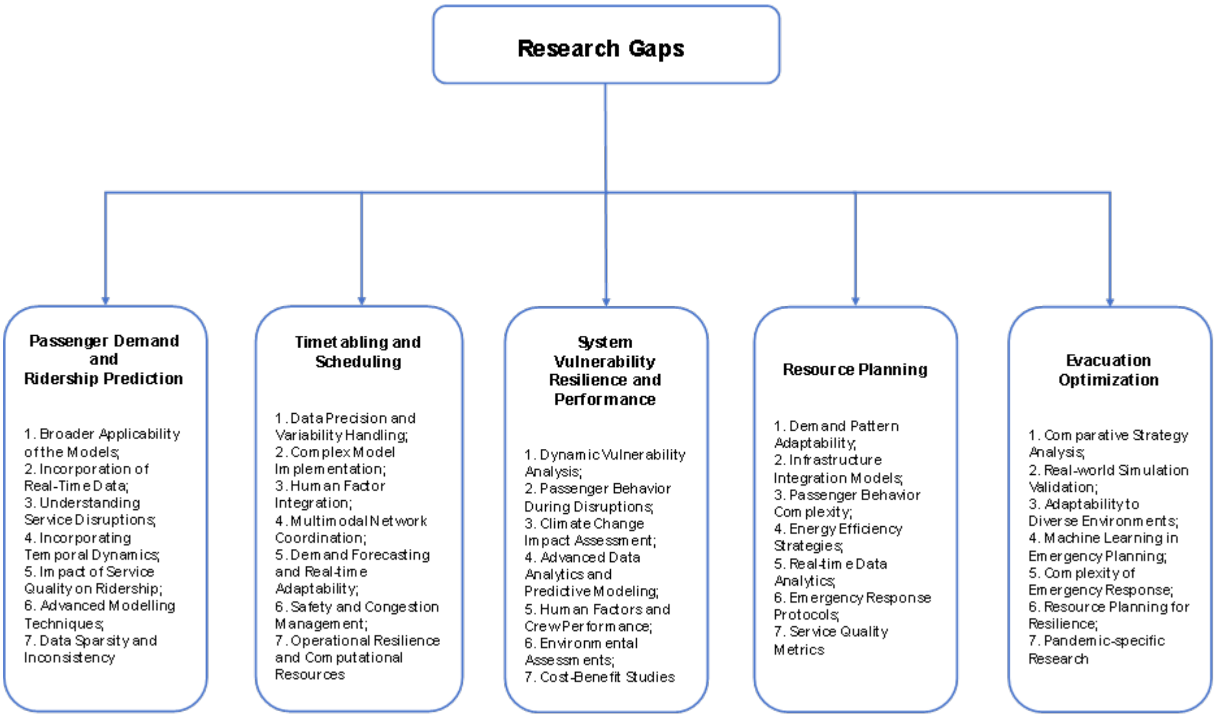

Figure 9. Research gaps.

accomplished by utilizing longitudinal data and time series analysis techniques to track the evolving relationships between demand and its determinants. The impact of service quality factors, such as travel times, crowding, and reliability, on passenger volume and route choice behavior should also be a subject of research inquiry. Additionally, research is required to tackle the challenges posed by data sparsity and inconsistency, especially in regions with limited data availability. This involves developing techniques to impute missing data and calibrate models that can perform robustly even with sparse or irregular inputs.

3.2 Timetabling and Scheduling

Future research in metro timetabling should aim to bridge the existing gaps by enhancing data precision, simplifying complex models, and improving the integration of human factors. There is a need for models that can adapt to real-world variability without compromising on accuracy or computational efficiency. The development of advanced data analytics and machine learning techniques can play a pivotal role in this respect, providing better forecasting and real-time adaptability for passenger demand and system performance. Additionally, research should focus on the practical challenges of multi-modal network coordination, ensuring seamless integration and synchronization across different transportation modes. This includes addressing the complexities of human decision-making in the context of timetable rationalization and the unpredictability of passenger behavior. Safety and reliability remain paramount, and future studies should explore innovative methods for managing congestion and ensuring safety on crowded lines, as well as developing robust rescheduling strategies that can quickly respond to disruptions and maintain system stability. Operational resilience is another critical area where future research can make a difference. This includes the development of hybrid approaches that leverage deep reinforcement learning and adaptive algorithms to optimize train and rolling stock scheduling, while also considering the computational resources required. Lastly, addressing the details of passenger experience and flow management is essential for improving overall service quality. Research should continue to refine timetabling methods that consider the trade-offs between efficiency and passenger comfort, particularly in the context of stop-skipping and multi-modal connectivity.

3.3 Metro System Vulnerability, Resilience and Performance

Future research in metro vulnerability, resilience and performance should build on the current literature by addressing its limitations and venturing into new territories. Researchers should aim to construct comprehensive reliability models that encapsulate the metro system's various components infrastructure, rolling stock, power systems, and signaling to grasp their interactions and their collective influence on performance. Dynamic vulnerability analyses should be carried out to consider the progression of system failures over time and the ripple effects of disruptions, encompassing the study of recovery mechanisms and the enduring resilience of metro systems. Understanding passenger behavior during disruptions is crucial; researchers should investigate changes in route choice, mode switching, and how perceptions of risk and safety evolve. Climate change's potential repercussions on metro system reliability and performance demand assessment, particularly in light of increasingly frequent and intense weather events, and fluctuating temperature patterns. Leveraging advanced data analytics and predictive modeling can transition maintenance strategies from reactive to proactive, with the goal of preventing failures in advance and streamlining maintenance schedules. Integrating real-time data from diverse sources, including social media, mobile phone data, and IoT devices, can deepen our understanding of passenger behavior and system performance in both regular and disrupted circumstances. Human factors and crew performance play a vital role in system reliability, necessitating research on the impact of fatigue, training, and decision-making during emergencies. Environmental assessments of metro systems should be conducted to devise strategies that minimize emissions, energy consumption, and waste, while upholding or enhancing system performance. Cost-benefit studies are essential to appraise the financial implications of investments in system reliability and performance improvements, factoring in intangible benefits such as heightened passenger satisfaction.

3.4 Resource Planning

Future research in metro systems resource planning should aim to address the identified gaps by enhancing the adaptability of models to diverse demand patterns and infrastructures. There is a need for more comprehensive case studies that can validate the applicability of algorithms and strategies across different urban rail transit systems. The development of advanced simulation techniques, possibly integrating machine learning and artificial intelligence, can play a crucial role in capturing the complexities of real-world passenger behavior and operational constraints. Additionally, research should focus on simplifying the models used for passenger flow control and energy optimization to make them more practical and computationally efficient. This includes exploring hybrid models that can balance the trade-offs between efficiency, service fairness, and robustness in the face of dynamic and unpredictable real-world conditions. The integration of human factors into metro system planning is another area that requires further investigation. This includes understanding how passengers make decisions in the context of metro operations and how these decisions can be incorporated into resource planning to improve overall system performance. Safety and reliability are paramount, and future studies should explore innovative methods for managing congestion, ensuring safety on crowded lines. This includes the development of hybrid approaches that leverage advanced analytics and adaptive algorithms to optimize rolling stock management. Lastly, research should continue to refine strategies that consider the trade-offs between efficiency and passenger comfort, particularly in the context of peak-hour operations and multi-modal connectivity.

3.5 Evacuation Optimization

Future research in urban metro systems must address several critical research gaps to enhance the resilience and efficiency of these networks. Firstly, there is a pressing need for comparative analyses that can objectively evaluate the effectiveness of various disruption management strategies, accounting for the diverse operational contexts of different metro systems. Additionally, the development of simulation models that closely mimic real-world conditions is essential to validate the practicality of proposed solutions, particularly in the face of dynamic disruptions and complex emergency scenarios. The adaptability of these models to diverse urban environments, including varying infrastructures and passenger profiles, is crucial for their widespread applicability. Integrating advanced machine learning techniques into emergency response planning can significantly improve the accuracy and adaptability of evacuation strategies, though the reliance on simulation data must be carefully considered. The practical challenges of implementing emergency response solutions, especially in complex scenarios like fires, need to be thoroughly explored to ensure the robustness of metro systems. These models should be designed to balance efficiency, service fairness, and robustness in the face of unpredictable real-world conditions. Research should also focus on the specific challenges posed by pandemics (and epidemics and endemics), including the development of strategies to maintain service levels and passenger safety during such health crises. Lastly, the integration of human factors into metro system planning is vital.

4 Conclusion

This paper studied literature in the last decade encapsulating the critical aspects of operations management for metro systems, highlighting the complexity and challenges in maintaining efficient and resilient urban transit networks. It captured the latest trends and findings in the field, with the aim to provide an understanding of the interrelated issues faced by metro systems. The analysis of passenger demand and ridership predictions underscored the need for models that could adapt to various network structures and demand patterns, integrating real-time data to enhance forecast precision. Timetabling and scheduling research has focused on developing robust optimization approaches to improving service quality and efficiency, yet challenges remain in the need for precise data, model complexity, and the dynamic nature of passenger demand. The section on metro system vulnerability, resilience and performance emphasized the importance of comprehensive reliability models and considered the interactions of various system components and the impacts of climate change and human factors. The resource planning category in metro systems underscores the necessity for integrated models that can optimize the allocation of resources. Meanwhile, the evacuation optimization research highlights the need for strategies that ensure system resilience during emergencies.

The paper not only synthesized the existing knowledge but has also identified the limitations of current scholarly works and knowledge gaps. The future research directions suggested encompassing the development of more robust and accurate models for passenger demand prediction, the construction of comprehensive reliability models that account for the dynamic vulnerabilities of metro systems, and the advancement of resource planning and evacuation strategies that leverage advanced analytics and optimization techniques. By focusing on these critical areas, future research can contribute to the development of sustainable and resilient metro systems that can adapt to the dynamic needs of growing urban populations while maintaining high standards of safety, reliability, and efficiency. This paper can serve as a useful reference for future studies and provide practical recommendations for metro operators and policymakers to enhance the performance and resilience of their systems.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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