Digital Twins for Traffic Congestion in Smart Cities: A Novel Solution Using Data Mining Techniques

Arianna Anniciello[a], Simona Fioretto[b], Elio Masciari[c] and Enea Vincenzo Napolitano[d]
Department of Electrical and Information Technology Engineering, University of Naples Federico II, Italy

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Abstract: This article serves as a position paper that explores the complex issue of traffic management in smart cities and the challenges it presents. The problem of urban traffic is particularly relevant in our modern world, where more and more people are moving to urban environments, leading to congestion, pollution and reduced quality of life. To address this challenge, we propose an innovative methodology based on Digital Twins. The paper proposes an extended approach that integrates Digital Twins with other existing techniques such as Trajectory Mining, Process Mining, and Decision Making. These techniques, which combine motion data, process analysis, and data-driven Decision Making, can enrich the Digital Twin model, provide a deeper understanding of traffic flows, and deliver more targeted and effective traffic management solutions. This proposal represents a significant step forward in the search for innovative and sustainable solutions for urban traffic management, and lays the foundation for further research and development in this critical area.

1 INTRODUCTION

In recent years, the concept of Smart Cities has emerged as a transformative approach to addressing the challenges of urbanisation through the use of advanced technologies, data analytics and intelligent infrastructure (Yin et al., 2015). Within the context of smart cities, one of the most pressing issues is urban traffic congestion, which poses significant challenges to transport systems and affects the quality of life of residents (Napolitano, 2023).

To address this issue, the use of Digital Twins(Batty, 2018) offers a novel and promising approach to provide comprehensive insights into traffic dynamics and support effective Decision Making. Digital Twins, as virtual representations of physical objects or systems, could integrate real-time data, simulation models and analytics to create a dynamic digital replica of urban transport networks (El Saddik, 2018). By applying Digital Twins, Smart Cities can gain valuable insights into traffic patterns, optimise traffic flow and develop intelligent strategies to alleviate congestion (Deren et al., 2021).

This paper aims to explore a novel application of Digital Twins to address urban traffic congestion in the context of Smart Cities. Specifically, it focuses on the use of Trajectory Mining, Process Mining and Decision Making techniques in this domain. The paper will explore the concept of Digital Twins and their role in addressing urban traffic congestion (Jiang et al., 2021). It will discuss how Trajectory Mining techniques can extract valuable insights from trajectory data collected from vehicles, pedestrians and other sources. In addition, it will explore the application of Process Mining techniques to analyse and optimise traffic flow by identifying bottlenecks and inefficiencies in transport systems (Rudskoy et al., 2021). Furthermore, the paper will highlight the importance of data-driven Decision Making supported by Digital Twins to enable effective congestion management strategies. By exploring the application of Trajectory Mining, Process Mining and Decision Making techniques within the framework of Digital Twins, this paper aims to contribute to the advancement of Smart City transport systems. It highlights the potential of these techniques to improve traffic management, reduce congestion and create more efficient and sustainable urban transport networks within Smart Cities.

2 RELATED WORK

In literature it is possible to find research studies which integrates Digital Twins with other supporting technologies, with the aim of empowering Digital

[a] https://orcid.org/0000-0002-0941-7481
[b] https://orcid.org/0009-0006-8700-8188
[c] https://orcid.org/0000-0002-1778-5321
[d] https://orcid.org/0000-0002-6384-9891

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Twins solutions.

In the domain of Process Mining applications (Van Der Aalst, 2012) that support Digital Twins, there exists a multitude of studies that focus on various application areas. In a recent study (Brockhoff et al., 2021), the combined utilization of Digital Twins and Process Mining is investigated, proposing their integration as a means to facilitate the utilization of data and models from future systems in real-time scenarios. Another publication (Beerepoot et al., 2023) explores the concept of "Digital Process Twins" , which represents the realization of Digital Twins specifically designed for what-if process analysis. This advancement would enable the development of sophisticated techniques for automating process optimization. In this context, automated process optimization refers to the ability to identify optimal interventions within a process to either maximize or minimize a given objective function. This objective function is typically defined in terms of one or multiple performance measures, while adhering to specific constraints. Furthermore, in the field of architecture, engineering, and construction industry, a study (Pan and Zhang, 2021) investigates the use of Process Mining in building information modeling (BIM). The authors propose a Digital Twin-based framework that integrates BIM, IoT, and Process Mining, serving as a practical method to effectively control and optimize complex construction processes with a high degree of automation and intelligence.

Several applications of Trajectory Mining and Digital Twins in Smart Cities can also be found in the literature.

(Yan et al., 2022a) proposed the use of Digital Twin technology to analyse and study the behaviour patterns of real drivers and pedestrians. Through the use of Digital Twins, a deeper understanding of traffic dynamics and human behaviour can be achieved, serving as a foundation for the development of advanced safety and mobility solutions.

In their comprehensive review, Jafari et al.(Jafari et al., 2023) emphasise the imperative of using state-of-the-art technology to detect real-time attacks in dynamically evolving transport systems. They highlight the vulnerability of human-centric transportation systems to data security threats, which necessitates the integration of Digital Twins technology to effectively detect and mitigate cyber and physical attacks. Consequently, the use of Digital Twins ensures the establishment of a safe and reliable environment for all stakeholders within the transportation domain. In particular, pedestrians, as an integral part of transport systems, warrant significant attention to ensure their health and safety.

Du et al. (Du et al., 2021) introduced a novel scheme for real-time trajectory prediction based on Digital Twins, specifically tailored for platoons of connected intelligent vehicles . By harnessing the power of Digital Twins, accurate and up-to-date information on vehicle trajectories within a platoon can be obtained, facilitating improved coordination and planning of actions between connected vehicles, ultimately leading to increased efficiency and safety.

In their study, (Yu et al., 2021) present a data-driven continuous trajectory modelling approach to construct a Digital Twin channel. The proposed methodology includes a data-driven modelling technique to accurately extract wireless channel characteristics in specific scenarios, coupled with trajectory modelling to efficiently capture the spatio-temporal correlations of the wireless channel as user equipment traverses it. These Digital Twin-based models provide enhanced capabilities for wireless channel characterisation, enabling improved wireless network design and performance optimisation in dynamic and complex environments.

Integration of Digital Twin methods in Decision Making has been proved in different studies, also considering application on transportation optimization. (Zhou et al., 2021) developed a DSS that explores Digital Twinning and simulation-optimization capabilities for resilience assessment with recovery action optimization. The Digital Twin replicates detailed port operations that cannot be captured through more traditional mathematical modeling approaches. Digital twinning also enables the modeling of uncertainty in the disruption events, as well as subsequent port recovery operations.

(Jiang et al., 2022) present an urban road planning approach based on Digital Twin, multi criteria decision making and geographic information system called DT-MCDM-GIS, highliting how Digital Twin methods can interpret various data into understandable expressions to assist urban road planning considering various factors, namely building demolition and land use, traffic congestion, driving route selection habit, air quality, and noise. (Neto et al., 2021) In this work, a Decision Support Systems (DSS) for opportunistic preventive maintenance scheduling is developed based on a Digital Twin framework. (Gao et al., 2022) investigate the application of Building Information Modeling and Digital Twins in the transportation industry, which indicates that the integration and utilization of multiple technologies can improve the schemes of mega engineering projects, improving the efficiency of such projects' digital management over their whole life cycle. We also believe that it is necessary to further improve the research

design and present the results as clearly as possible in a future study. (Feng et al., 2023) study explores the application of Digital Twins in Intelligent Transportation Systems and establishes an innovative transportation platform based on Digital Twins. It investigates the influence of the transportation network's adaptability on travel behavior by examining how uncertain events impact travelers' travel conditions. Furthermore, a travel behavior model is developed to enhance the effect of traffic conditions on travel by considering the impact of uncertain events, particularly in multi-modal transportation, such as customized public transportation. The study also addresses the issue of data sharing in the Internet of Vehicles (IoV) traffic system from the perspective of Digital Twins. To overcome the limitations of data sharing in Blockchain technology in the IoV, an LPMADDPG algorithm is proposed and applied to optimize data sharing. Finally, a Digital Twins Blockchain traffic system is established and experimentally verified. Their results demonstrate that the IoV system based on Digital Twins reported here significantly optimizes data sharing and improves the ability of the transportation network to withstand and repair the impact of external uncertainty on the transportation system. Besides, it saves more than 50 % of the communication overhead and improves operational efficiency by nearly 20 % over traditional algorithm.

3 DIGITAL TWINS FOR SMART CITIES

As cities continue to grow, the challenges associated with urban living are also expanding. To address these issues, the concept of Smart Cities has emerged, which involves the integration of innovative technologies to make cities more intelligent and efficient. Among the various challenges faced by cities, transportation management is a crucial aspect that requires attention. It involves the promotion of sustainable transportation options, the development of intelligent public transportation systems based on real-time information, the implementation of traffic management systems (TMSs) to mitigate congestion, and the incorporation of safety and environmentally friendly applications. To tackle these transportation-related challenges in future Smart Cities, researchers have been actively focusing on utilizing advancements in sensing, communication, and dynamic adaptive technologies. These efforts aim to enhance the efficiency of existing road TMSs, enabling them to effectively address the issues that arise in the context of evolving cities. (Djahel et al., 2014) discuss the importance of leveraging these technologies to make transportation management systems more efficient in the context of Smart Cities. One approach that has gained attention in this field is the use of Digital Twins. Several authors, including (Kumar et al., 2018) have explored the application of Digital Twins in managing traffic congestion. The concept behind the Digital Twin is to create a virtual representation or image that corresponds to a physical asset, such as vehicles or road infrastructure. By creating a Digital Twin of these assets, it becomes possible to monitor and manage their real-time status, behavior, and performance. This virtual representation can provide valuable insights into traffic patterns, identify congestion points, and enable proactive decision-making to alleviate congestion and enhance overall transportation management in Smart Cities (Kumar et al., 2018). The integration of Smart Cities involves the use of innovative technologies to address the challenges associated with urban living. Transportation management is a key area of focus, and the utilization of Digital Twins offers a promising approach to effectively manage traffic congestion by creating virtual representations of vehicles and road infrastructure. These Digital Twins enable real-time monitoring and Decision Making, contributing to more efficient and sustainable transportation systems in Smart Cities (Kumar et al., 2018).

3.1 Conceptual Framework

A Digital Twin is a virtual version of an object or system that spans its lifespan, is updated from real-time data, and aids Decision Making through simulation, Machine Learning, and reasoning. By analysing evolving client preferences, modifications, and experiences, Digital Twin is already assisting firms in staying ahead of digital disruption (Javaid and Haleem, 2023).

The conceptual framework for Digital Twin technology involves three core components: the physical asset, the digital representation, and the connection between them. (Liu et al., 2021)

- Physical Asset:
  The physical asset refers to the tangible entity in the real world that is being represented by the Digital Twin. In the context of traffic management, it could be a transportation infrastructure, such as roads, highways, intersections, traffic signals, or vehicles.
  The physical asset generates data through various sensors, devices, and monitoring systems, capturing real-time information about its status, performance, and environmental conditions.

- Digital Representation:
  The digital representation is the virtual counterpart of the physical asset created within the Digital Twin environment. It is constructed by integrating and analyzing data collected from the physical asset and other relevant sources.
  It aims to accurately replicate the physical asset's characteristics and behaviors.
  The digital representation consists of several key elements:
  - Geometric Model: It represents the physical asset's spatial dimensions, topology, and layout. This includes the shape, size, location, and connectivity of roads, intersections, and other transportation infrastructure elements.
  - Data Integration and Analytics: Various data sources, such as sensor data, traffic flow information, weather data, and historical records, are collected and integrated into the digital representation. Advanced analytics techniques, such as machine learning and data mining, are applied to gain insights and extract patterns from the data.
  - Simulation and Modeling: The Digital Twin incorporates simulation and modeling capabilities to replicate the behavior of the physical asset under different scenarios. This enables what-if analysis, predictive modeling, and optimization of traffic flow, congestion management, and other key performance indicators.
  - Real-time Data Synchronization: The Digital Twin continuously receives and updates real-time data from the physical asset to maintain its accuracy and relevance. This synchronization ensures that the digital representation reflects the current state of the physical asset and enables real-time monitoring and decision making.
- Connection and Interaction:
  The connection between the physical asset and its Digital Twin is a fundamental aspect of Digital Twin technology. It enables bidirectional communication and interaction between the physical and virtual realms. Through this connection, real-time data from the physical asset is fed into the Digital Twin, while insights, predictions, and optimized solutions derived from the Digital Twin can be applied to improve the performance and management of the physical asset. This connection facilitates continuous monitoring, analysis, and decision making based on the Digital Twin's insights and recommendations.
  The interaction between the physical asset and its Digital Twin forms a closed-loop feedback system:
  - Data Collection and Integration: Real-time data from the physical asset, such as traffic volumes, speed, and environmental conditions, is collected, processed, and integrated into the Digital Twin.
  - Analysis and Decision Making: The Digital Twin analyzes the collected data, applies advanced analytics techniques, and generates insights, predictions, and recommendations for traffic management decision making.(Semeraro et al., 2021)
  - Action and Control: Based on the insights and recommendations from the Digital Twin, appropriate actions can be taken in the physical world. This may involve adjusting traffic signal timings, rerouting vehicles, implementing congestion management strategies, or optimizing infrastructure planning.

4 INTEGRATED APPROACH TO DIGITAL TWIN TECHNOLOGY FOR TRAFFIC MANAGEMENT

Since Digital Twins are virtual representations of physical entities or complex systems such as buildings, transportation networks, infrastructures, or even entire cities, using Trajectory Mining and Process Mining in conjunction with Digital Twins can provide several benefits and applications in Smart Cities.

- **Trajectory Mining.** One of the main applications of Trajectory Mining (Zheng, 2015) with Digital Twins could be traffic (Xu et al., 2023; Costa et al., 2014) and transport optimisation. By analysing the trajectories of both private and public vehicles within a city, traffic patterns, critical points, congestion and flow issues can be identified (Fan et al., 2022; Zhang et al., 2023). This information can be used to identify areas for improvement, such as adjusting traffic lights, optimising routes or introducing new infrastructure. In addition, Trajectory Mining can contribute to the implementation of intelligent traffic management systems that can adapt to road conditions in real time (Tong et al., 2020).
  Trajectory Mining with Digital Twins can also contribute to public safety in Smart Cities. By analysing the trajectories of people or objects, such as emergency vehicles or suspicious individuals, anomalous behaviour or risky situations can be identified. This information can be used to

improve emergency management, detect critical situations such as traffic accidents or suspicious activities in a timely manner, and assist law enforcement and emergency services in making decisions.

- **Process Mining.** Process Mining is a field of research which focuses on the extraction of processes from available event logs in Information Systems. Digital twin and Process Mining are two different field of research, but many studies proved the efficacy of their joint application. (Brockhoff et al., 2021) affirms that especially process discovery from runtime data, conformance checking, and process prediction using process models at runtime are increasingly important aspects to systematically improve the operation of Digital Twins. Process mining can play a crucial role in supporting Digital Twins for traffic congestion management in smart cities, however very few works apply PM to urban mobility. Currently, the topic was discussed by (Jadrić et al., 2020) who applied in a case study process mining in smart mobility. In addition, it was found that the research mostly involved implementation of smart parking solution, and highlighting the gap between the potentiality of the application and the existing studies. A recent study (Delgado and Calegari, 2023) assess with a real case study the suitability of process mining for the analysis of urban mobility problems obtaining promising results in this research.
  Given the lack of studies in process mining supporting Digital Twins in the context of traffic congestion, we believe that there are some available open solutions using the potentiality of process mining and that could be explored. Some of the possible application of the technique could include traffic patterns identification identifying bottlenecks, and gain insights into the causes of congestion in specific areas of a city, optimizing traffic management strategies can help city authorities identify the most efficient traffic management strategies to reduce congestion and improve traffic flow. In addition process mining can be used to simulate and evaluate the impact of infrastructure changes(Fioretto, 2023), such as the addition of new roads, traffic lanes, or public transportation routes.
- **Decision Making.** Digital Twins facilitate data-driven Decision Making by providing a holistic and real-time view of the urban transportation system, offering improved situational awareness to traffic management stakeholders. By integrating and analyzing data from various sources, Digital Twins enable Decision Support Systems (DSS) tools to provide insights, predictions, and recommendations based on real-time and historical data analysis. Let us delve the advantages of an Intelligent Decision Support Systems that leverage Digital Twin technology. The integration of data from various sources, including sensors, cameras, and historical records, provide a comprehensive view of the urban transportation system. Advanced analytics techniques applied within the Digital Twin environment allow for the identification of trends, patterns, and correlations in traffic data. The Digital Twin of the physical transportation system is not able to support the different management processes solely, such as resource allocation or infrastructure maintenance, as it is not containing information concerning orders, products, schedules, company specific priorities and further data that is necessary to control said processes. Therefore, the Twin must be integrated into a suitable decision support system (Kunath and Winkler, 2018). When integrated data meets real time collection, real-time monitoring becomes a reality. By continuously synchronizing with real-time data feeds, the Digital Twin reflects the current state of the physical asset of the Urban Transportation System. Ding et al (Ding et al., 2023) designed a Decision Support System based on Digital Twin and Big Data technologies and demonstrate how real-time monitoring and an integrated decision support can be established. Decision support tools, such as interactive dashboards and scenario analysis interfaces, enhance the understanding and interpretation of complex traffic data and allows traffic management in Smart Cities to have an up-to-date understanding of traffic conditions, incident occurrences, and operational metrics. Furthermore, Digital Twins can generate recommendations based on the analysis and modeling within the Digital Twin, suggesting optimal strategies which decision makers can explore, assessing the potential outcomes, and make informed but timely decisions, providing quick responses to changing traffic conditions. Some situations may require instant intervention, especially when a standard protocol has been designed for identified pattern. Digital Twin facilitates the generation of alerts and notifications based on predefined thresholds or abnormal events detected within the connected environment. Through real-time data analysis and comparison with established patterns, the Digital Twin can identify traffic incidents, congestion buildup, accidents, or abnormal traffic behavior.

When such events occur, the Digital Twin can trigger automated alerts to designed users, such as traffic operators, emergency responders, or maintenance personnel, enabling them to take immediate action and implement appropriate response measures. Real-time data synchronization and analysis also allow for the early detection of incidents or abnormal conditions. Upon detecting such events, the Digital Twin can automatically generate recommendations for response strategies (d'Ajello et al., 2022), such as rerouting traffic, adjusting signal timings, or dispatching emergency services. These proactive responses help minimize the impact of incidents, reduce congestion, and improve safety by facilitating swift and coordinated actions. The use of Digital Twins for traffic management provides also resource management and maintenance benefits. (Yan et al., 2022b) findings reveal that data analytics and the visualized enterprise Digital Twin system offer better practices for strategic management decisions in the dynamic and constantly changing business world by providing a constant and frequent adjustment on every decision that affects how the business performs over both operational and strategic timescales. By leveraging real-time data and predictive modeling, Smart Cities can enhance situational awareness, enabling optimized resource allocation in traffic management. The insights and recommendations derived from the Digital Twin facilitate efficient deployment of traffic control measures, such as adaptive signal timing, dynamic lane management, and incident response strategies. By identifying areas of high traffic demand or recurring bottlenecks, resources can be strategically allocated to address these specific areas, resulting in a more effective utilization of infrastructure and services. Additionally, Digital Twins provide a platform for proactive maintenance and infrastructure management, allowing for predictive maintenance planning, optimized repair schedules, and efficient allocation of maintenance resources. These factors collectively enable proactive responses and efficient allocation of resources, and contribute to improved operational efficiency and reliability of the transportation system. Digital Twin technology also promotes collaborative Decision Making among different stakeholders, including traffic engineers, city officials, and citizens, by providing a platform for information sharing, communication, and participation. The adaptive nature of Digital Twins allows for iterative improvements and adjustments based on real-time data and feedback. Traffic engineers, city officials, and citizens can access the Digital Twin platform to provide input, voice concerns, and contribute suggestions. This participatory approach allows for a diverse range of perspectives and expertise to be considered, leading to more informed and inclusive Decision Making. Stakeholders can review proposed strategies, evaluate potential impacts, and provide feedback, enhancing the overall effectiveness and acceptance of decisions. Digital twins are also inherently adaptive, allowing for iterative improvements and adjustments based on real-time data and feedback. The Digital Twin continuously synchronizes with real-time data from the physical asset, updating the digital representation accordingly. This real-time feedback loop enables stakeholders to monitor the impact of implemented measures, assess their effectiveness, and make adjustments as needed. By analyzing the real-time data within the Digital Twin, stakeholders can identify areas for improvement, fine-tune strategies, and adapt to changing conditions or emerging challenges. The iterative nature of Digital Twins supports a continuous learning and improvement cycle, enhancing the effectiveness of decision making over time.

In summary, this technology enhances decision making by providing timely and accurate information, facilitating efficient resource allocation, and improving the overall management of urban transportation systems in Smart Cities. It promotes collaborative decision making by enabling information sharing, stakeholder engagement, and participatory processes. The ability to simulate and evaluate alternative scenarios within the Digital Twin environment further enhances decision-making capabilities, enabling stakeholders to assess the potential impacts of various strategies before implementing them in the physical world. The adaptive nature of Digital Twins allows for iterative improvements and adjustments based on real-time data and feedback, fostering continuous learning, optimization, and alignment of decisions with the evolving needs of the transportation system and its stakeholders in Smart Cities.

5 CONCLUSIONS

In conclusion, this position paper has examined the application of Digital Twins in addressing urban traffic congestion within Smart Cities. Authors have presented a compelling argument for the adoption of Digital Twins as a transformative technology for traffic

management, highlighting their potential to provide comprehensive insights and support effective decision making. Digital Twins offer a promising solution to the pressing issue of urban traffic congestion by integrating real-time data, simulation models, and analytics to create dynamic digital replicas of urban transport networks. This technology enables Smart Cities to gain a holistic view of traffic dynamics, optimize traffic flow, and develop intelligent strategies to alleviate congestion. By leveraging Digital Twins, cities can enhance their transportation systems, improve quality of life for residents, and move closer to their goals of sustainability and efficiency. Throughout the paper, authors have advocated for the adoption and further exploration of Digital Twins in traffic management. The integration of Trajectory Mining, Process Mining, and Decision Making techniques within the Digital Twin framework presents exciting opportunities to optimize traffic management strategies, predict traffic patterns, evaluate infrastructure changes, and enhance public safety. By embracing Digital Twins, Smart Cities can embrace innovative approaches and leverage advanced technologies to tackle the complexities of urban traffic congestion. In summary, Digital Twins have the potential to revolutionize traffic management in Smart Cities, paving the way for more efficient, sustainable, and livable urban environments. While challenges and considerations exist, such as data privacy and security, infrastructure requirements, and stakeholder engagement, the benefits offered by Digital Twins outweigh these obstacles. It is essential for policymakers, urban planners, and researchers to recognize the transformative power of Digital Twins and work collaboratively to harness this technology's full potential in shaping the future of traffic management in Smart Cities. By embracing Digital Twins, we can build smarter, more connected, and more efficient urban transportation systems that enhance the quality of life for residents and pave the way for a sustainable future.

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