Leveraging Digital Twin Technology for Enhanced Railway Digitalization to Improve Malaysian Economy

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2023 IEEE 21st Student Conference on Research and Development (SCOReD) | 979-8-3503-1882-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/SCOReD60679.2023.10563431

***Abstract* – The 21st century has brought significant technological advancements, notably in the railway sector to cater for escalating passenger and freight needs. Malaysia recognizing the importance of railways in goods, services and passenger transit, has committed RM95 billion in 2023 towards transportation infrastructure. Amidst this, the digital twin concept has gained traction. The Internet of Things (IoT) combined with a digital twin, a virtual interactive replica of a tangible object or process allows for effective data monitoring and real-time visualization. Such tech integration promises enhanced railway system monitoring, predictive analysis, operational efficiency, and safety. For instance, IoT sensors on tracks can identify defects through vibrations. NVIDIA Omniverse spearheads this digital shift offering tools for comprehensive railroad digitalization. By assimilating sensor data with tools like OpenStreetMap and datasets from platforms such as Google Earth, a comprehensive railway digital twin can be created. The deployment of digital twin technology is anticipated to yield substantial economic dividends for Malaysia enhancing trade, employment, and national development. Given the burgeoning digital twin market, Malaysia is poised to optimize its railway industry potentially becoming a major transportation nexus in Southeast Asia. This synergy of technology and economic strategizing augurs well for Malaysia's future rail development.**

Keywords – Digitalization, Digital Twin, Economic, Malaysia, Railway, Nvidia Omniverse, IoT

I. INTRODUCTION

In the realm of contemporary technological advancements, the 21st century has borne witness to unparalleled transformations across various sectors. The railway industry historically pivotal in global travel is no exception to these paradigm shifts. Due to its long history, railways had to change to evolve in tandem with the increasing demand for both passenger and freight transportation. Malaysia a burgeoning economy is ardently developing its railway infrastructure currently spanning 1,655 kilometres.

According to Knoema's data [1], this commitment to transportation infrastructure development is further cemented by a record allocation of RM95 billion in 2023 as reported by Malaysia's Ministry of Finance [2]. The railway system is intrinsically a cornerstone of national transportation infrastructure executing the paramount task of transporting goods, services, and individuals.

Enhancements in efficiency, safety and reliability of railway infrastructure can yield tangible economic benefits. For instance, anticipated improvements in the urban railway network in Kuala Lumpur's vicinity are projected to contribute to an economic impact worth 213 billion Ringgit in Malaysia over the ensuing decade [3].

Fig. 1. Malaysian Railway Network [4]

Concurrently, the transportation sector is not immune to the wave of digitization and its growing economic impact. A salient offshoot of this digitization is the emergence of digital twin, innovative tools facilitating the simulation and prediction of individual manufacturing processes and overall enterprise behaviour. The remarkable advancements over recent decades in digital technologies and computational power combined with cost reductions in their deployment have rendered digitization a ubiquitous phenomenon pervading all societal and economic domains. Indeed, digital twins have become quotidian realities. The market for digital twins is forecasted to reach an astounding USD 110.1 billion by 2028 [5].

In the digital age marked by the fourth industrial revolution (IR 4.0), the world is entering an era of data-driven solutions and interconnected systems. Therefore, the railway digital twin can play a significant role in the development of Malaysian transport infrastructure offering unprecedented opportunities to visualize, analyze and optimize the entire railway ecosystem. The digital twin could be a valuable tool to improve the performance, efficiency and reliability of the Malaysian communication and transport sector.

This can help address the challenges faced by the sector and boost economic growth. Railroad simulation can help with resource planning, forecasting, risk management and safety through real-time monitoring and traffic optimization.

This study examines the method of creating a digital twin, its functionality and how it can theoretically help improve the economic aspect of the Malaysian transport industry.

II. Literature Review

A. The Concept and Development of Digital Twin

The rapid advancements in digital technology alongside decreasing computational costs have spurred the widespread adoption of digitalization across various societal and economic sectors particularly exemplified by the concept of the "digital twin". This phenomenon popularized post-Grieves' 2017 publication [6] is no longer exclusive to technical systems but also penetrates the economic sphere reflecting the growing digitization of the economy. Michael Greaves, in his scholarly contributions, delineated three distinct types of digital twins: the Digital Twin Prototype (DTP), the Digital Twin Instance (DTI) and the Digital Twin Environment (DTE). DTP represents the archetype of a physical product encompassing a wealth of information necessary for its tangible replication ranging from intricate 3D models to disposal methodologies. The DTI on the other hand mirrors a specific real-world entity retaining a persistent linkage to its physical counterpart throughout its existence and may include detailed 3D models, historical and current components data, production processes, and service records. Lastly, DTE serves as a comprehensive platform that supports both predictive and interrogative functionalities thereby facilitating anticipatory product behaviour analysis and in-depth exploration of specific instances respectively. Rudskoy, Ilyin and Prokhorov [7] conducted an in-depth study of the largest digital twins in Intelligent Transport Systems (ITSs). Drawing on the ArchiMate notation methodology and using the city of Chelyabinsk as an example, the authors highlight the transformation of potential digital twins in predictive motion analytics. They define three main functions of ITSs namely: digital twin traffic simulation, strategic traffic light control and holistic management of transport network. Another inclusion of this study is the Chelyabinsk system, which includes data from various sensors that manage traffic lights and help in city planning.

In the paper by Samuel Rundel et al. [8], the authors endeavour to integrate City Information Models (CIMs) with simulation software accentuating their pertinence in facilitating informed decision-making within urban environments particularly concerning crowd and traffic simulations. Primarily the exploration is anchored on the latest generation of 3D CIMs derived from urban-scale geospatial information. These models capacitate a gamut of urban activities from planning to the analysis of vulnerabilities. However, one major issue that concerns us is that many digital twins are not feasible for small municipalities because of how complex their data and infrastructure requirements are. To contravene this, the authors proffer an innovative framework that endeavours to ameliorate the convolution inherent in digital twins but without eschewing comprehensive simulation capabilities. Their avant-garde proposition interlinks the traffic simulation SUMO with the Unity Game Engine utilizing the TraCI middleware for visualization enabling an encompassing framework to function on an isolated computer expeditiously.

Distinctly diverging from conventional digital twins which oftentimes necessitate fresh data accumulation through costly methodologies like LiDAR, this modus operandi leverages pre-extant public data thus effecting a notable reduction in expenditure. The assimilation of data from diverse sources particularly OpenStreetMap (OSM) is adeptly managed via the “SafeFME” software culminating in a commendably precise data representation. This dataset subsequently informs the creation of a 3D model through tools such as Esri CityEngine. Notwithstanding its abridged complexity, the proffered framework manifests intrinsic intricacy with the authors conceding the absence of comprehensive user evaluations at this juncture. To conclude, while the manuscript presents a laudably innovative approach to traditional CIM conundrums, it underlines the imperativeness for further iterations and assiduous evaluations to ascertain its real-world viability.

B. Application of Digital Twins in Transportation Systems

Rimskaya and Anokhov's [9] article offers a comprehensive examination of the role of digital twins in transport economics. They emphasize the importance of interpreting collective data as an “organized complex” for better decision-making. By introducing a three-level information system, the authors highlight the evolution from basic application data to more deterministic information. This work underscores the profound impact of digitalization on the transport sector advocating for a customer-centric approach in a rapidly evolving digital age.

A study by De Donato et al. [10] highlights the growing relevance of digital twins in the rail industry. They emphasized the importance of digital twins by referencing ongoing standardization activities and illustrating how they can be utilized across various railway assets such as trains, signalling systems and infrastructures. The authors combine Artificial Intelligence (AI) and digital twins, underlining their potential to shift current maintenance practices towards continuous and predictive modes. Preliminary guidelines and reference architecture are introduced for the realization of AI-assisted digital twins with a focus on predictive maintenance. The paper provides a broad overview of relevant literature categorizing selected papers on digital twins in railways with a specific emphasis on the combination with AI. Machine learning, intelligent sensor data integration, data mining and computer vision are discussed as key components of the technology. Challenges in the design, implementation, and characterization of AI-enhanced digital twins are acknowledged and a first architecture is proposed for predictive maintenance. The work serves as an essential contribution towards the digital integration with AI in railways offering insights, guidelines and a foundational architecture that may guide future research and development in the field.

In the article "Digital Twins in Railways", Ruth Dirnfeld [11] addresses the growing interest in digital twins within the railway industry. She underscores the lack of systematic reviews on the implementation and benefits of digital twins in railways. Dirnfeld discusses the potential of AI especially in the domains of maintenance, safety, and planning. Citing Bešinović et al., she highlights the importance of marrying AI with railway transport, pointing to applications like image processing for visual inspection and AI for fault diagnosis. She also touches upon the role of AI in station security, traffic planning, asset management and passenger services. Furthermore, Dirnfeld delves into digital twins’ enablers emphasizing the significance of AI techniques like machine learning in harnessing the full potential of digital twins. She also mentions the pivotal role of IoT, AR/VR, and hardware advancements in digital twins’ development.

C. Economic Impact of Railways

In Shi's [12] empirical study, the impact of High-Speed railways (HSR) on regional economic growth in China is analyzed. The study highlights that HSR has compressed the space-time distance between cities catalyzing trade flows, market expansion, and knowledge spillover sharing. An intriguing observation from the study is the contradictory impact of HSR on different regions where well-connected regions benefitted economically however less connected areas were marginalized economically. Moreover, HSR facilitated an increase in the urban permanent population indicative of a shift from rural to urban areas. Shi concludes by emphasizing the long-term effects of HSR on regional economic development suggesting that its full potential may be realized in synergy with improvements in the institutional environment, human capital and technical education levels. Another study highlighted the key role that the development of the rail transport system plays in Malaysia's economic growth trajectory.

According to empirical research, there is a strong correlation between growth in economic activity, Gross Domestic Product (GDP) and Gross National Income (GNI) especially after the announcement of certain railway development projects. Projects such as the KL-Singapore High Speed Rail (HSR) are expected to make a significant contribution potentially boosting the gross national product by RM100 billion upon completion. Similarly, the East Coast Rail Link (ECRL) project conceived as part of the Pan-Asian rail network, is designed to boost international trade links and increase Malaysian GDP by about 1.5% annually over the next 50 years. As the transport sector plays a critical role in Malaysia's global economic status, investment should continue highlighting the significant economic benefits of expanding Kuala Lumpur's connectivity in terms of savings in time, energy and money.

Work accomplished in [13] presented a comprehensive analysis of the drivers and barriers to the growth of the digital economy in Malaysia. The authors highlight that the government's 2020 budget is an important catalyst to boost the technology industry, improve digital infrastructure and encourage e-commerce which could contribute up to RM40 billion to Malaysia's GDP by 2021. In addition, initiatives such as the Digital Free Trade Zone (DFTZ™) and the development of the FinTech and e-commerce sectors are noted as tools to promote cross-border trade and strengthen Malaysia's digital economy. On the other hand, the paper also outlines serious challenges such as a lack of technological innovation, rising cybersecurity threats and potential job losses that could hinder the full realization of the digital economy in Malaysia. The authors conclude that while advances in digital technology have created significant opportunities, significant efforts need to be made to overcome existing barriers and risks.

III. OBJECTIVES

The main objectives of implementing the digital twin for the Malaysian railway system are:

- Real-time Monitoring: Keep a constant watch on the railway fleet's operational status, track conditions and other vital parameters ensuring that all components function within their prescribed limits.
- Predictive Analysis: Analyze data trends and patterns, and anticipate potential issues or malfunctions before they escalate to allow proactive interventions.
- Optimized Maintenance: Schedule maintenance activities based on real-time data and predictive insights to maximize the life and efficiency of railway assets and reduce downtimes.
- Safety Enhancements: Monitor critical safety parameters continuously to identify and rectify any discrepancies ensuring the utmost safety for passengers and railway staff.
- Operational Efficiency: Use real-time data to adjust and optimize train schedules, routes and speeds to guarantee timely service and maximise fleet utilization.
- Resource Allocation: Ensure optimal deployment and use of resources from train fleet to manpower based on current demands and predicted trends.

As a result, the digital railway can keep track of train work analysis and reporting, forecast and schedule work, resolve conflicting train situations, regulate traffic in the event of traffic failures, assign orders and tasks to stations and locomotives, build optimal traffic routes, and modify train schedules.

IV. DIGITAL TWIN

The digital twin is a software analogue, a virtual interactive copy of a real object or process. It simulates the technical characteristics and behavior of the original in various situations such as the appearance of interference and environmental influences. Working with a digital twin is similar to managing the life cycle of the main object.

In the railway system, the digital twin displays the operation of the entire fleet of railway trains. The digital twin of the rail network is a valuable decision-support tool for train fleet maintenance.

With modern digital twins, industrial and transportation facilities can be visualized in real-time and brought "to the millimetre" closer to the original. Typically, digital twins are created for certain areas of production. Sometimes they cover the full cycle of operation of a transport facility or enterprise. Digital models use data from hundreds to thousands of remote sensors. It is necessary to decide in advance on the methods of obtaining incoming data, methods of storage and the optimal model for analysis. The digital twin in the railway is a model that most accurately describes the real cause-and-effect relationships between production, economic, financial, and organizational indicators.

The railway represents a paramount embodiment of tangible assets. The infrastructure of a railway comprises a comprehensive range of components including but not limited to tracks, switches, signalling systems, hump yards and rolling stock. The primary economic function of railroads is the conveyance of tangible commodities such as wheat, steel, ore and livestock. Thus, railways serve as tangible assets facilitating the movement of other tangible assets. Within the paradigm of the digital railway, it becomes imperative to delineate the tangible components that will be incorporated into the digital twin simulation of the Malaysian railway system.

Considering the physical assets, it is possible to provide a visualized model image of a complex technical system. The technology makes it possible to acquire models with additional degrees of freedom leading to the possibility of reconstructing multidimensional variations of the potential states of the fleet and the railway track.

Table 1. Physical Assets

Physical Asset Category	Specific Assets
Track Infrastructure	- Rails - Turnouts - Crossings - Speed limits
Rolling Stock	- Locomotives - Trains - Freight cars - Passenger cars - Service vehicles
Stations & Buildings	- Platforms - Depots
Signaling & Communication	- Signal lights - Track circuits
Bridges & Tunnels	- Viaducts - Underpasses - Tunnels

Each physical asset is preferably equipped with sensors. A digital twin equipped with up-to-date data can reflect everything that happens on the railway more accurately and reliably.

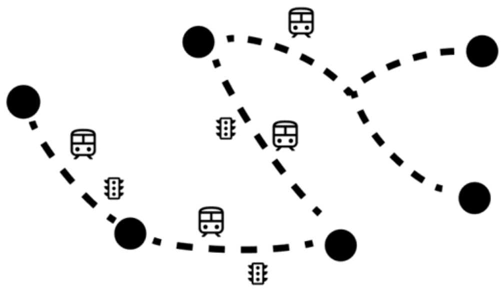

Fig. 2. Basic Railway Structure

In the context of the Internet of Things (IoT) advancements in Malaysia's transportation sector, the nation's rail transport infrastructure comprises diverse systems ranging from heavy rail (exemplified by KTM Komuter) to light rapid transit (LRT), mass rapid transit (MRT), monorail systems, airport rail links and a specialized funicular railway system. The heavy rail system serves intercity passenger and freight transportation requirements in addition to certain urban public transportation. On the other hand, the rapid transit systems including LRT and MRT, predominantly facilitate intra-city urban mobility within Kuala Lumpur and the extended region of Klang Valley [14].

All the components of the railway system such as rolling stock and locomotives, infrastructure elements, individual cargo units, security systems, electronic displays, and surveillance cameras, can be connected via IoT to create an effective and well-functioning mechanism. IoT is used to monitor the railway infrastructure e.g. tracks, rails, turnouts, traffic lights, etc. Sensors are installed on the railways to transmit temperature values. Considering the infrastructure of the Malaysian railway and its extensive network of railways (LRT, monorail, freight railways) from an economic point of view, it is not profitable to install sensors on each section of the railway. Such sensors are designed to transmit important data and register anomalies, wear patterns and changes in the environment and the railway itself. For example, it is possible to install sensors to detect vibration and sound on railway tracks and depending on the sound of passing rolling stock or the vibration it causes, it can detect defects in both the tracks and the train itself [15].

In the same way, a train equipped with GPS sensors and speed control devices provides the digital twin with accurate data. This technology makes it possible to control their movement and location. This is evident from the recent initiative by Keretapi Tanah Melayu Bhd (KTMB) where they launched their mobile app 'MyRailtime' giving commuters real-time location updates for its train services in the central region [16]. This service was made possible due to Global Positioning System (GPS) devices installed on all trains to monitor the locations of KTM Komuter trains along specified routes as well as the express train service between key stations.

Stations and associated edifices are fortified with a myriad of surveillance systems, environmental monitoring sensors, and footfall detection mechanisms. The assimilation of this data equips the digital twin with insights facilitating optimal passenger flow management, the reinforcement of safety measures during high-traffic intervals and the timely commissioning of infrastructural maintenance endeavours.

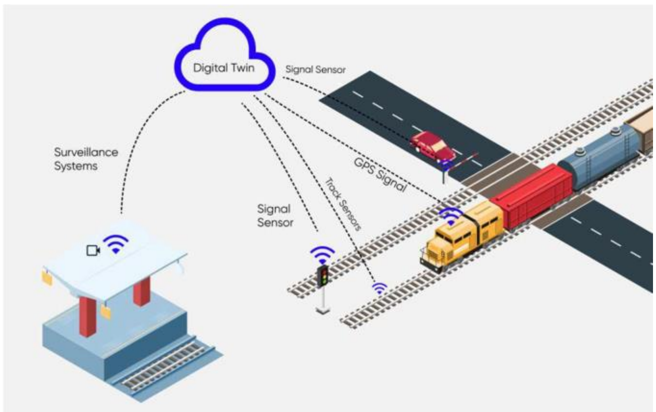

Fig. 3. Railway signals example

V. DIGITAL TWIN ENGINE (NVIDIA OMNIVERSE)

The digital revolution in the rail sector is a harbinger of transformative change with a particular focus on the Malaysian economic landscape. A key component of this metamorphosis is the paradigm of the digital twin. In this context, NVIDIA Omniverse provides an unparalleled opportunity to increase the digitalization of railroads.

For example, the Deutsche Bahn, with a length of 33,000 km which unites 5,700 stations has created a digital twin using omniverse technology [17].

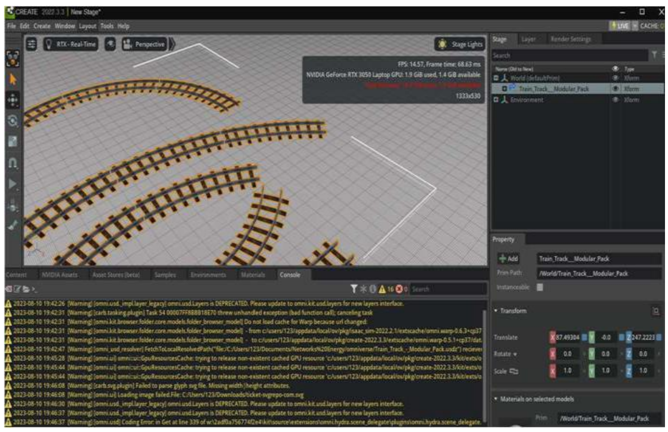

Fig. 4. Nvidia Omniverse Create Interface [18]

The NVIDIA Omniverse Kit [18] is a set of tools for building Omniverse applications and microservices. It is based on a core platform known as Carbonite providing a wide range of features through a set of lightweight extension modules. NVIDIA Omniverse Create is a virtual world creation application that lets model, assemble, light, and render large-scale scenes. It was created using the NVIDIA Omniverse Kit. The scene description and model in memory are based on the USD format. Omniverse Create uses advanced USD-based workflows such as Layers, Variants, Instances, and more. Combined with MDL-formatted materials and an NVIDIA RTX-based renderer running on NVIDIA RTX-enabled graphics cards to create visually appealing and physically accurate worlds. Omniverse Create integrates PIXAR's Hydra framework and, therefore can be used to display USD content in any renderer that supports the Hydra framework (e.g. Storm, Embree, PRMan, etc.). Real-time world creation for multiple applications and advanced collaborative workflows among Omniverse users is possible when connected to the Omniverse Nucleus server. Since the omniverse system is very flexible and allows to creation of extensions and connects via API, it is possible to integrate sensor data from the railroad IoTs cloud directly into the digital model.

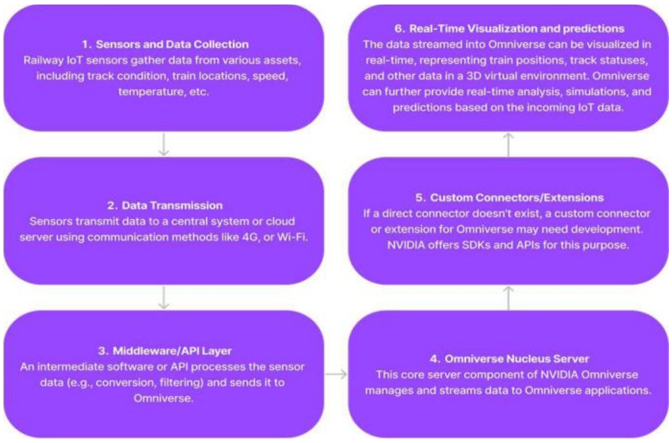

Fig. 5. Steps to integrate real-time data from railway IoT sensors into NVIDIA Omniverse

In the pursuit of comprehensively mapping and analyzing the Malaysian railway infrastructure, it is imperative to leverage open data repositories. A prime example of such a database is OpenStreetMap (OSM), an expansive geographical information system that precisely records railway attributes. Within the OSM lexicon, a gamut of terminologies elucidates railway types and affiliated infrastructures. This spans from primary railway tracks denoted as rail to specialized subsets encompassing subways, trams, narrow-gauge railways, and light rail transit systems. Additionally, tracks no longer in active use are catalogued as disused. Beyond linear transportation roads, the OSM database encapsulates crucial infrastructural components such as railway platforms, central railway hubs or stations, designated tram stops, and even pivotal transition points like crossings.

To augment this two-dimensional data with depth and realism, one might consider integrating topographic datasets derived from platforms like Google Earth [19]. Such datasets proffer a granular representation of the earth's surface enabling a holistic visualization. A pioneering method to enhance this visualization is the strategic installation of cameras aboard trains. This not only captures real-time spatial data but also paves the way for the generation of a dynamic three-dimensional rendering of the railway environment.

VI. ECONOMIC EFFECTS

The implementation of digital twin technology in railway digitalization offers promising economic returns for the Malaysian economy. Considering device and maintenance costs, the deployment of multi-sensor track scanners can lead to substantial financial savings for railroads by preventing potential track and roadbed issues with a feasible payback period of two years [20]. Economically financing major infrastructure like railways requires a delicate balance between cost-benefit analysis and potential economic spillovers impacting society [21]. Railways particularly in congested infrastructures, present significant operational cost challenges [22]. While many governments globally prioritize social returns over financial returns for public transport infrastructure, it is undeniable that public transport including railways plays a pivotal role in stimulating trade, enhancing competitiveness, and ensuring long-term national growth [23] [24].

Sustainable policies for railway infrastructure largely hinge on sustainable financing which has implications for employment, GDP growth, and broader monetary and fiscal policies [21] [25]. Investing in transport infrastructure has ripple effects on land use and production processes [25]. It is crucial to explore various financing methods from tax increment financing to private finance to optimize the government's budget [24]. While social policies around transportation focus primarily on economic and environmental concerns, it's essential to recognize their broader impact on areas like health, housing, and employment. The dynamic nature of transportation within the socio-technical system underscores the importance of stakeholder engagement to ensure that societal needs are addressed comprehensively during infrastructure development [28].

Enterprises can generate data arrays and optimize physical processes using digital twins and AI, which opens up new possibilities for innovation in the creation of new services and business models. Digital twins make it possible to implement research differently by reducing time and costs. In 2019, Gartner named the digital twin as one of the ten disruptive technologies that have changed the world. The digital twin market across all industries is cumulative $6B and is projected to grow at an all-time high with a Compound Annual Growth Rate (CAGR) of 40% to reach $23B by 2023 [26]. Thus, the Peugeot joint-stock company (PSA Group) estimates a reduction in production costs of around 50% over the period from 2015 to 2020 due to the replacement of physical work with digital twins on test benches [27] [29].

Malaysia is an emerging economy looking to move up the value chain and drive growth in the era of IR 4.0 with the advent of digital twin technology. Using the growth trajectory of the global digital twin market, the Malaysian railway sector can not only optimize its operational efficiency but also become the hub of railway digitalization in the Southeast Asia region. In addition, public-private partnerships combined with policies that encourage innovation can ensure that Malaysia fully benefits from these developments by strengthening its position in the global economy. Ultimately, Malaysia will be able to improve the efficiency and profitability of the railways by optimizing processes through their simulation and monitoring in real-time. In addition, developed rail transport can attract tourists visiting the country. In general, several new technologies in the industry generate employment opportunities thus attracting new knowledge to the country and creating foreign investments.

VII. CONCLUSION

In today's era marked by rapid technological transformation, the rail industry is a symbol of constant evolution and adapting to the growing demands of our world. Malaysia's fervent efforts to expand its rail infrastructure underlined by massive financial commitments symbolize the country's progress in this area. With the digital revolution sweeping through all industries, the rail sector is on the cusp of significant change, especially in the Malaysian economy.

The digital twin, the computational twin of material systems is emerging as a beacon of this coming shift. Platforms like NVIDIA Omniverse have ushered in a new era of rail digitization offering real-time data integration and visualization capabilities. In addition, the development of a digital clone is inevitable with the creation of the IoTs infrastructure and the modernization of the existing railway. Open-source databases such as OpenStreetMap further expand the rich palette of information available for integrated rail infrastructure mapping.

From an economic perspective, the potential benefits of integrating digital twin technology are enormous. In addition to operational efficiency, railroads equipped with these advanced digital systems can bring huge economic benefits. The promise of significant returns by the potential savings from proactive maintenance and streamlined operations is a compelling case for its adoption. The broader socio-economic implications such as promoting trade, increasing employment, and generating holistic national growth emphasize the importance of the digital twin in railway. Given Malaysia's aspirations in the era of IR 4.0, the use of digital twin technology can not only optimize its rail operations but also establish the country as a beacon of railway digitalization in the Southeast Asia region. The intertwining of the public and private sectors coupled with an innovation-driven policy will be a catalyst for Malaysia's growth in this area. In conclusion, the combination of technological advancement and economic foresight will not only transform Malaysian railways but also create a promising trajectory for the country's future.

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