Digital Transformation in Road Maintenance Management: Drivers, Barriers and a Readiness Framework

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ABSTRACT:

Road maintenance management is important for ensuring the sustainability of infrastructures, road safety, and effective transportation systems. Nevertheless, the current issues faced by road agencies include inadequate resources, aging assets, fragmented data environments, and increasing maintenance demands. In this regard, digital transformation can be viewed as an opportunity for improving maintenance activities and managing assets more efficiently. This study aims to identify the drivers and barriers associated with digital transformation initiatives and to develop a Digital Readiness Framework for Smart Road Maintenance Management. To achieve that, the conceptually driven methodological framework was selected to critically examine and analyse available literature on such topics as digital transformation, road maintenance management, smart infrastructures, Building Information Modelling (BIM), Internet of Things (IoT), digital twins, data governance, and asset management. Specifically, thematic analysis technique was used for grouping the findings of the conceptual review into three categories: drivers of digital transformation, implementation barriers, and dimensions of digital readiness. Overall, four drivers were highlighted including improved operational efficiency, enhanced decision-making process using data analytics, improvement of services offered, and sustainable infrastructure management. In turn, four implementation barriers included organizational problems, human resource limitations, technological constraints, and finance and governance constraints. Using findings from the literature review, a Digital Readiness Framework for Smart Road Maintenance Management, which includes organisational readiness, human readiness, technological readiness, and policy readiness, was formulated. The proposed model underscores the connection between transformation drivers, implementation challenges, and the readiness factors necessary for facilitating effective digital transformation. It is evident that digital transformation involves more than mere technology uptake and calls for a comprehensive understanding of organisational, human, technological, and policy requirements necessary to make digital transformation feasible. The proposed framework provides valuable insights into the topic of digital transformation in infrastructure management and can be used by road organisations to adopt innovative road maintenance management practices.

Keywords: Digital Transformation; Road Maintenance Management; Smart Infrastructure; Digital Readiness Framework; Asset Management

INTRODUCTION

Road infrastructure acts as a major facilitator to economic growth, socio-economic development, and overall well-being due to providing access to the market, medical care, education, and jobs among others. Road infrastructure can be viewed as a large component of the construction sector, which has played a key role in national development and regional integration. It is therefore important to maintain roads in good condition. This is because road maintenance helps in the extension of infrastructure lifespan as well as ensuring efficiency and safety of the road transport system [1], [2], [3].

In spite of all this, road maintenance management still poses various challenges especially for developing nations. Limited funding, aging assets, growing need for maintenance, and limited technological capabilities

have often restricted road maintenance agencies from undertaking their maintenance programs effectively. Traditional road surface monitoring systems usually involve a lot of investment, technical expertise, and effort, which is why many road agencies depend on decisions that are not scientific. Such practices are likely to cause inefficient management of resources, delay in maintenance activities, poor road surfaces, and high maintenance costs. Additionally, other governance factors like ineffective planning, limited finances, contractor selection issues, and ineffective administration have continued to influence road maintenance management programs [4], [5], [6].

To address these issues, scholars and experts have attempted to develop analytical methods which will facilitate maintenance activities and decision-making process. Different optimisation as well as multi-criteria decision-making models, such as MOO, Fuzzy Analytical Hierarchy Process (Fuzzy AHP) and Fuzzy Technique for Order Preference by Similarity to Ideal Solution (Fuzzy TOPSIS), have been employed by road authorities to help them choose appropriate maintenance strategies. This allows road authorities to consider multiple criteria for maintenance activities at once, prioritising costs, condition of the pavement, safety issues, environmental aspects and socio-economic implications [1], [2], [7].

These developments have seen the increasing complexities of road infrastructure systems leading to the incorporation of digital technologies in road maintenance management. Various technological applications, including GIS, building information modelling (BIM), Internet of Things (IoT), digital twins, and smart road infrastructures, are increasingly being employed with regard to monitoring infrastructures, maintenance operation planning, assets management, and decision-making. GIS tools help in conducting spatial analysis and prioritizing maintenance operations. Similarly, the use of BIM helps in documentation, life-cycle management, and scheduling of maintenance operations. Meanwhile, IoT, digital twins, and smart road infrastructures facilitate real-time monitoring and thus make it possible to conduct predictive maintenance [8], [9], [10].

However, the incorporation of digital tools brings various benefits that range from improved maintenance practices, sustainable infrastructure development, road safety, as well as optimization of available resources. Intelligent road ideas include the use of sensing capabilities, communication solutions, and intelligent transport systems to improve the efficiency of operations and lay a foundation for future connected and autonomous transportation environments. However, there are certain challenges associated with the introduction of digital transformations in roads. Current research on this topic identifies some of the major issues as fragmented data environment, interoperability problems, lack of training of asset managers, technological integration issues, limited funding, and policy conflicts. Moreover, such factors as data quality, trust, and governance still affect decision-making systems [11], [12], [13].

Although past research has made considerable efforts to investigate individual digital tools and methods for maintenance optimization, the existing body of knowledge has mostly been preoccupied with technical considerations and efficiency gains. Little effort has been dedicated to exploring the organizational, human capabilities, governance, and technology readiness conditions necessary to achieve digital transformation within road maintenance organizations. In addition, there is a lack of conceptualization concerning the main drivers, inhibitors, and technology readiness dimensions of digital transformation within road maintenance management literature. Therefore, this study aims to identify the key drivers and barriers influencing digital transformation initiatives and to develop a Digital Readiness Framework for Smart Road Maintenance Management.

METHODOLOGY

The research methodology adopted in this study is a conceptual review approach, which was employed to explore the current state of digital transformation in road maintenance management and to develop a Digital Readiness Framework for Smart Road Maintenance Management. A conceptual review is an effective research strategy, particularly for synthesising the existing body of literature and establishing relationships among key concepts and themes [14], [15]. Consequently, it makes sense for the study of digital transformation in road maintenance management.

To ensure a structured and transparent literature identification process, a search strategy was developed using the Scopus database. The search was conducted using keywords related to digital transformation, digital

readiness, smart infrastructure, digital technologies, and road maintenance management. The search parameters applied in this study are presented in Table 1.

Table 1. Search Strategy

Parameter	Description
Database	Scopus
Search Field	TITLE-ABS-KEY
Search String	("digital transformation" OR "digital readiness" OR "smart infrastructure" OR "digital twin" OR BIM OR IoT) AND ("road maintenance" OR "road asset management" OR "highway maintenance" OR pavement)
Publication Period	2021–2026
Subject Areas	Engineering, Computer Science, Social Sciences
Document Types	Articles, Review Papers, Conference Papers
Language	English

The retrieved records were subsequently filtered based on publication year, subject area, document type, and language to ensure the relevance and quality of the selected literature sources. The results of the literature search and screening process are summarised in Table 2.

Table 2. Literature Search and Screening Results

Screening Stage	**Records**
Initial search results	628
After publication year filter	524
After subject area filter	475
After document type filter	399
After English language filter	380
Studies selected for detailed review	35

The inclusion criteria consisted of studies written in English language between 2021 and 2026, addressing digital transformation, digital readiness, smart infrastructure, digital technologies of road maintenance and infrastructure asset management. Non-relevant articles, non-English studies, duplicates, and studies with limited relevance to the research were excluded. The chosen articles were evaluated against the eligibility criteria according to their titles, abstracts, and full texts' relevance. Articles that studied digital transformation, digital readiness, smart infrastructure, digital technologies, and infrastructure asset management were selected. Lastly, 35 articles were included in further analysis. Thematic analysis was used to identify patterns and recurring ideas in the literature. The identified themes were further grouped into three main categories that covered drivers, barriers and dimensions of digital readiness that were the basis of creating the Digital Readiness Framework.

To improve transparency and demonstrate how the reviewed literature contributed to the development of the proposed framework, a summary of the key studies, their focus areas, contributions, and associated themes is presented in Table 3.

Table 3. Summary of Key Studies and Themes Related to Digital Transformation in Road Maintenance Management

Author(s)	**Study Focus**	**Key Contribution**	**Primary Theme**
Soni & Saini (2025)	Smart Infrastructure and Digital Transformation	Digital technologies improve operational efficiency, asset performance, and infrastructure management.	Drivers
Maletič et al. (2023)	Digital Transformation in Asset Management	Identified key drivers, barriers, and organisational requirements for digital transformation.	Drivers & Barriers

Li & Fu (2026)	Digital Infrastructure and Sustainability	Digital transformation supports operational efficiency and sustainable infrastructure management.	Drivers
Basnet et al. (2023)	Predictive Maintenance	Digital technologies enable proactive maintenance and resource optimisation.	Drivers
Setty & Devpura (2024)	Asset Management Capabilities	Highlighted challenges related to asset inventory, planning, and system integration.	Barriers
Zheng et al. (2025)	Data Requirements and Digital Transformation	Emphasised data interoperability and information management requirements.	Barriers
Aleca & Mihai (2025)	Digital Infrastructure and Industry 4.0	Demonstrated the role of digital skills and technologies in organisational productivity.	Drivers
Permatasari et al. (2026)	Organisational Digitalisation	Highlighted organisational capabilities, leadership, and workforce readiness.	Digital Readiness
Das (2024)	Smart Cities and Governance	Demonstrated the relationship between digital transformation, governance, and service delivery.	Drivers & Barriers
Consilvio et al. (2023)	Digital Twin for Road Maintenance	Enabled predictive maintenance and intelligent decision support.	Drivers
Gao et al. (2025)	Digital Twin Infrastructure Management	Highlighted lifecycle monitoring and digital readiness requirements.	Digital Readiness
Shirwa et al. (2025)	Digital Governance Framework	Emphasised governance, stakeholder coordination, and institutional readiness.	Barriers & Digital Readiness
Nagy et al. (2026)	Digital Technologies in Construction and Roads	Identified technology adoption barriers and workforce competency requirements.	Barriers
Ortega-Del-Rosario et al. (2025)	AI Adoption and Regulatory Frameworks	Highlighted financial, governance, and regulatory challenges.	Barriers
Suprun et al. (2024)	Digital Transformation Maturity Assessment	Proposed digital readiness dimensions for infrastructure asset owners.	Digital Readiness

Drivers Of Digital Transformation in Road Maintenance Management

The key drivers for digital transformation in road maintenance management include the need to optimize the performance of the infrastructure, make better decisions, improve services, and manage assets sustainably. According to the existing literature, there is an increased use of digital technology by road organizations in solving their operational challenges and improving infrastructure results. The identified key drivers for digital transformation include operational efficiency, evidence-based decision-making, service quality improvement, and sustainable infrastructure management.

Operational Efficiency

Operational efficiency is one of the main factors contributing to digital transformation within road maintenance management systems. By implementing digital technologies, organisations are able to increase the efficacy of resource usage, operational efficiencies, and asset performance across the entire infrastructure lifecycle. In such

a way, integrated digital systems allow organisations to not only save operational costs but also significantly enhance the maintenance process as well as project performance [16], [17].

Moreover, digital transformation leads to higher operational efficiency through better allocation of resources, productivity growth, and innovations capabilities. Digital infrastructure contributes to eco-efficient operations through optimising business processes and increasing the efficiency of an entire system [18]. Regarding the road maintenance sphere, the implementation of proactive maintenance strategy through digital technologies allows organisations to perform preventive maintenance activities, which leads to lower costs, disruption minimisation, and improved safety results as compared to traditional reactive approach [19].

Data-Driven Decision Making

Data-driven decision-making is regarded as an important force that drives the process of digital transformation in road maintenance management by helping organizations to optimize their planning, monitoring, and operational control capabilities through proper utilization of relevant data and analytics. The provision of asset inventories, asset condition assessment databases, maintenance scheduling, and asset performance reporting through the use of digital asset management systems help infrastructure organizations to make appropriate investment decisions and optimal maintenance plans [20]. The ability of organizations to have accurate and updated data about assets makes the process of maintenance decision-making more robust as they can utilize condition assessment data for performance-based decision making [21]. Furthermore, digital transformation helps in facilitating the planning and performance evaluation processes in infrastructure management through evidence-based decision-making processes [17], [18].

Intelligent technologies have contributed significantly towards the increased use of data-driven techniques in managing infrastructure. Examples of such technologies include artificial intelligence (AI), Internet of Things (IoT), big data, machine learning, cloud computing, and digital twin technology, all of which allow organizations to collect and analyse data to enhance their decision-making processes [22], [23]. Such techniques have been shown to provide valuable insights to organizations in terms of prediction, trends analysis, and performance appraisal to help improve resource optimization and strategic planning abilities [24]. For instance, in the case of road maintenance, the use of digital inspection tools and decision-making support through the digital twin concept enables predictive maintenance by analyzing infrastructure data to identify suitable interventions given available resources [25].Taken together, all these aspects illustrate how data-driven decision-making is crucial in the digital transformation process of road maintenance management.

Service Quality Improvement

The improvement of service quality is yet another critical motivator towards digital transformation in road maintenance management. Digitalization helps in improving the quality of services provided through optimizing operation management, enhancing accessibility, and facilitating interactions between the organization and customers through advanced technological tools [24].The use of digital platforms, smart systems, and process automation makes it possible to have effective and fast monitoring and management practices, thereby increasing operational efficiency and satisfying stakeholders [23], [24]. Besides, through customer-oriented digital transformations, organizations can become more aware of the needs of users and provide more efficient, responsive, and reliable services [23].Through the use of Industry 4.0 technologies, made possible by cloud computing and digitalization, service quality can be further improved in terms of better resource management, increased service availability, and responsiveness to changes in the operating environment [22]. Road maintenance management can benefit from digitalization and modern methods using Pavement Management System that provides for continuous evaluation and maintenance activities on pavements [19].

Sustainable Infrastructure Management

Management of infrastructure sustainably has emerged as an essential catalyst for digital transformation within the area of road maintenance management as organizations aim at increasing the resilience of infrastructure, optimizing the use of resources, and improving asset performance. The deployment of technologies such as IoT, AI, BIM, digital twins, and big data analytics can aid in the planning, monitoring, and management of

infrastructure across its lifecycle [24]. More specifically, digital twin technologies can be used for lifecycle monitoring, maintenance, real-time performance evaluation, and optimization of resource utilization, thus allowing for the identification of possible infrastructure failures and implementing necessary interventions [26]. Smart technologies can further be utilized by road agencies for better maintenance planning, increased life of assets, and improved reliability of infrastructure [16].

In addition to organisational improvement, digital transformation can also be instrumental in achieving sustainability goals in terms of improved environmental performance and efficient use of resources. Sustainability is promoted through digital transformation through effective utilization of resources, innovation for green technology, and optimization of industrial systems [18].With the application of technologies such as cloud computing, IoT, artificial intelligence, blockchain, and analytics, companies are able to minimize wastage of materials and energy, conduct environmental monitoring, and embrace the principles of a circular economy [22]. Moreover, digital technologies enable organisations to improve their predictive analysis and make more informed decisions, thus balancing economic progress and environmental conservation in the process [18], [23].

Barriers To Digital Transformation in Road Maintenance Management

Although digital transformation may yield many benefits, the adoption of digital technologies for road maintenance management is difficult because of numerous barriers that have emerged. Road authorities are still struggling to apply digital solutions in their current road maintenance operations owing to limited resources, poor skills, disjointed systems, and organizational obstacles. As per the analysis of previous literature, there are four main barriers, comprising the context organizational, human, technological, and financial and governance.

Organisational Challenges

The issues related to the organisational level present one of the major obstacles in achieving digital transformation in the field of road maintenance management. Digital maturity is attainable via extensive organisational transformation, which includes not only the adoption of technologies but also changes to organisational structures, business processes, leadership styles, and work culture [16].Some of the obstacles currently faced by organisations include lack of a digital transformation strategy, insufficient awareness about the importance of asset management on a strategic level, and the reluctance to introduce changes within an organisation [17].In addition, inefficient asset inventorying, insufficient documentation procedures, a reactive approach to maintenance, and the lack of digital maturity impede operational efficiency and the implementation of asset management systems [20].

Additionally, the success of digital transformation would depend on stakeholder coordination, governance framework, and institutional adaptation. Lack of coordination among the involved parties can create fragmented activities, inefficiency in resource management, and poor implementation of digital transformation programs [27]. Infrastructural organizations often face challenges in aligning their digital efforts within their current operational, structural, and managerial systems, hindering transformation processes and implementation outcomes [24]. Furthermore, the presence of bureaucratic organizational structures, inadequate transformational leadership, and reluctance towards institutional changes still limit digital transformation within many organizations [23].Thus, addressing these organizational challenges would require more than technological innovations; they also need organizational restructuring and strategic alignment.

Human Resource Limitations

However, human resource-related constraints pose a significant challenge to the successful implementation of digital transformations in road maintenance management. The lack of digital competence, technical capabilities, and training is an obstacle to the adoption and exploitation of technologies by organisations [27]. Numerous organisations still struggle with a lack of staff with sufficient knowledge regarding emerging digital technologies, while limited understanding of digital trends and managerial support are also factors hindering the involvement of human resources in the digital transformation process [17]. Human resource limitations are one of the major barriers to the successful implementation of advanced maintenance and asset management in the context of road assets management. The same problem can be observed in the construction industry, whereby professional

capability deficiencies prevent efficient use of BIM technology, artificial intelligence, digital twins, and other digital solutions related to data analytics [28].Finally, the deployment of sophisticated analytical tools and techniques, for example, machine learning models, require specific capabilities and technical competence in data science that numerous organisations currently lack [19].Consequently, strengthening workforce capabilities through continuous training, skills development, and knowledge enhancement is essential for supporting successful digital transformation initiatives.

Technological Constraints

Technological barriers continue to pose a challenge to digitalization in road maintenance management. For any digital transformation to be successful, digital technology requires sufficient digital infrastructure and interoperable systems, among other factors. Unfortunately, many organisations still encounter numerous difficulties related to inadequate interoperability of information systems, lack of proper digitization, and failure to properly integrate asset management, financial, and GIS systems, leading to ineffective sharing of data [20].Likewise, the lack of proper data structure and interoperability tends to contribute to creation of information silos, making it hard for digital transformation projects to be effective [21].

There are also constraints that are linked to the limited adoption of new technologies within specific organisational functions and stages of the infrastructure lifecycle. Emerging technologies like Building Information Modelling (BIM), the Internet of Things (IoT), artificial intelligence (AI), and digital twins are often implemented in an independent way leading to lack of interoperability and continuity of data through the whole lifecycle of the asset [16]. Moreover, many organisations encounter challenges related to integration of the existing systems with digital technologies. Poor digital infrastructure and limitations related to technology standardisation further impede transformation process [21].Therefore, building technological infrastructure, enhancing its interoperability and creating a standardised digital environment become important steps to successful transformation.

Financial and Governance Challenges

Despite advancements made in the use of digital technology, finance still remains one of the biggest obstacles in implementing digitalization of road maintenance management. One of the reasons why the adoption of digital technologies has been slow is because of issues relating to uncertainty in cost-benefit analysis, costly implementation processes, lack of financing, and underdeveloped digital infrastructure [29]. Such challenges are even more pronounced within organizations that have limited financial capabilities as large amounts of money are needed in acquiring technology, building infrastructure, hiring manpower, and integrating systems. Road maintenance organizations within many developing nations have continued to face funding shortages which have contributed to their inability to carry out effective road maintenance practices [30].

Challenges associated with governance are yet another reason why it may be difficult to implement the processes involved in the process of digital transformation. Poor governance structures, disjointed policies, insufficient policy coordination, and inefficient regulation are among the key sources of uncertainty discouraging broad-scale technological implementation [29]. In the field of road maintenance, governance-related problems such as corruption, inadequate planning, inefficient project implementation, and poor institutional arrangements have been established as important contributors to the suboptimal functioning and sustainability of infrastructure [30]. The ongoing threats associated with data privacy, cybersecurity, intellectual property protection, and the lack of standardization further hinder efforts to successfully transform organizations with the help of technology [28], [29].

Digital Readiness Framework for Smart Road Maintenance Management

The success of digital transformation in organisations will require adequate levels of digital readiness that cut across a number of factors apart from technology usage itself. From the literature review above, it emerges that digital readiness refers to organisational ability, human ability, technological capacity, and the policy environment that determine the success of digital transformation efforts. From the analysis of the reviewed

literature, a digital readiness model for smart road maintenance management is proposed with the following four dimensions:

Organisational Readiness

Organisational readiness is an essential requirement for the success of digital transformations in road maintenance management. Organisational readiness goes beyond digital technology and covers strategy, leadership involvement, governance, organisational culture, human capacity, and information management processes that together make transformation possible [31]. For a successful transformation, digital strategies have to be aligned with the organisation's strategy to ensure that technological investments serve the organisation's purpose in the long run [16]. An organisation has to develop its digital strategy, asset management framework, and governance processes to facilitate digital transformations [17]. However, organisations often face financial constraints, lack of human resources, uncoordinated assets, and reactive approaches, all of which limit digital adoption and effectiveness in planning [20].

Moreover, for a successful digital transformation, there needs to be a coherent planning process, cooperation among stakeholders, integration of management systems, and organisational alignment in terms of its functions [18], [24]. The alignment of the organisational structure, policies, governing frameworks, and change management processes will assist in supporting digital transformation goals and help achieve sustainable implementation [27], [32]. Leadership commitment, organisational adaptability, knowledge management capacity, and continuous learning are some other factors essential in ensuring organisational readiness and supporting technology adoption [23]. Moreover, for the success of any digital transformation initiative, the combination of information coming from asset management systems, inspection technologies, maintenance management systems, and operational databases needs to occur on one unified platform that will allow organisations to make informed decisions [25].Hence, organisational readiness forms a basis for the implementation of digital transformation.

Human Readiness

Human readiness is one of the essential aspects of digital readiness as the successful deployment of digital transformation greatly relies on the adaptive capacity of employees and managers towards technology changes. Human readiness refers to the development of digital skills through consistent training and education, knowledge management and cross-functional cooperation in relation to transformation projects [31]. The successful deployment of digital solutions involves an appropriate level of knowledge, skills and expertise associated with technology, but a lack of skills may significantly affect digital transformation initiatives [20], [27]. Moreover, human readiness is not only about the technical skills, but also concerns stakeholder participation and social system involvement, as well as the openness of employees towards new technologies and approaches [32].In turn, organisations which allocate resources for workforce development by using training programmes and professional development activities can be more efficient in relation to digital transformations [17]. For example, the case study related to the road asset management demonstrates that initiatives aimed at capacity building, conducting research and learning result in increased workforce efficiency, improved maintenance planning and better use of digital tools. Therefore, human readiness is essential for ensuring that digital transformation initiatives can be effectively adopted, implemented, and sustained over the long term.

Technological Readiness

Technological readiness can be considered a critical component of digital readiness, as any digital transformation process requires the presence and development of digital technologies along the entire infrastructure lifecycle stage. According to the existing research, it is stated that technologies like IoT, artificial intelligence, cloud computing, big data analytics, digital twins, BIM, and intelligent asset management are crucial to providing the technological basis for implementing data-driven approaches to infrastructure management and making decisions [17], [26], [31]. These technologies help to implement monitoring and predictive analysis, intelligent decision-making, and performance evaluations that allow optimising resource consumption [18], [24]. Organisations having better technological readiness will have more chances for implementing advanced digital approaches and innovations [23].

Apart from the issue of availability, technological readiness requires adequate digital infrastructure, system integration, and integration of digital platforms within the processes of an organization. Infrastructure organizations continue to experience problems relating to fragmented information systems, under-utilization of digital platforms, and lack of integration of asset management systems, financial management systems, and GIS which limit effective data exchange and decision-making [20]. Consequently, the importance of adequate digital infrastructure which includes internet connectivity, cloud-based systems, IoT and advanced data platforms cannot be overlooked for digital transformation efforts to succeed [22].In road infrastructure, for example, the integration of BIM, IoT, artificial intelligence, machine learning, UAVs, digital twins, and intelligent monitoring systems have brought about efficiency in planning, monitoring, predictive maintenance, and management [28]. Furthermore, technologies such as Digital Twins provide simulation, monitoring, control, and decision-support functions using real-time infrastructure data [25].Thus, technological readiness can be described as a critical enabling factor for smart road maintenance management.

Policy Readiness

The aspect of policy readiness becomes integral to digital readiness because of the need for policies that can facilitate digital transformation. Scholars suggest that policy readiness includes the creation of standardized frameworks, data, and cybersecurity policies, as well as information and data governance frameworks that can make it possible for organizations to exchange information in an effective manner [26], [31]. Standardization is especially critical in data exchange and infrastructure management systems where it makes it easier for organizations to manage their digital assets effectively [21].Besides, policy readiness demands the integration of various regulations and standards, along with governance frameworks, to support technology adoption and collaborations [27], [32].

Besides regulatory readiness, policy readiness includes government intervention, institutional flexibility, and strategic action that make the conditions conducive for digital transformation. Suitable regulations, policies, frameworks, and guidelines can assist organizations in dealing with potential risks, ensuring compliance, and implementing new digital technologies [17].However, such regulatory barriers as inconsistent policy execution, ineffective governance structures, lack of adequate guidelines for emerging technology, and regulation can be deterrents to digital transformation [23], [29].In light of this problem, governments can aid digital transformation by means of innovative policies, collaboration between public and private sectors, investments programs, taxation policies, education programs, and digital infrastructure [22].As a result, policy readiness enables regulatory, governance, and institutional conditions necessary for sustainable digital transformation [18], [29].

Proposed Digital Readiness Framework

As per the analysis of the literature reviewed, a Digital Readiness Framework for Smart Road Maintenance Management is suggested to facilitate the effective adoption of digital transformation projects among road maintenance organisations. This digital readiness framework will comprise three main components that have been identified through an analysis of the reviewed literature – the factors that drive digital transformation projects, barriers to implementation of the projects, and the dimensions of digital readiness. The digital readiness framework makes an assumption that road organisations have the intent to pursue digital transformation to gain improved efficiency, effective data-based decision-making, high-quality services, and sustainable infrastructure management.

In order to address these barriers, road maintenance organisations should be ready in four different dimensions that are highly interconnected: organisational readiness, human readiness, technological readiness, and policy readiness. The aspect of organisational readiness relates to such issues as strategic alignment, leadership commitment, governance, and organisational culture. Human readiness highlights skills, digital literacy, training, and capacity building. Technological readiness deals with the presence of digital infrastructure, integration and interoperability, and modern technologies that help in managing assets intelligently. Lastly, policy readiness involves regulatory, data governance, cybersecurity standards, and collaboration at an institutional level.

The framework suggests that by improving on these four areas of readiness, the implementation of smart road maintenance management systems will be accomplished. Consequently, road agencies will be able to realize

increased efficiency in operations, better decisions based on data, better service provision, and sustainable infrastructure management results. The model is thus providing a comprehensive basis for future digital transformation efforts in road maintenance organizations.

Unlike existing digital transformation and digital readiness frameworks that primarily focus on general infrastructure organisations or industrial sectors, the proposed framework specifically addresses the context of road maintenance management. The framework integrates digital transformation drivers, implementation barriers, and readiness dimensions into a single conceptual model. This integration provides a sector-specific perspective that supports road agencies in assessing their preparedness for digital transformation while considering organisational, human, technological, and policy-related factors.

The framework illustrates the relationship between the key drivers and barriers of digital transformation and the four readiness dimensions (organisational, human, technological, and policy readiness) required to achieve smart road maintenance management outcomes, including improved operational efficiency, enhanced data-driven decision-making, improved service quality, and sustainable infrastructure management.

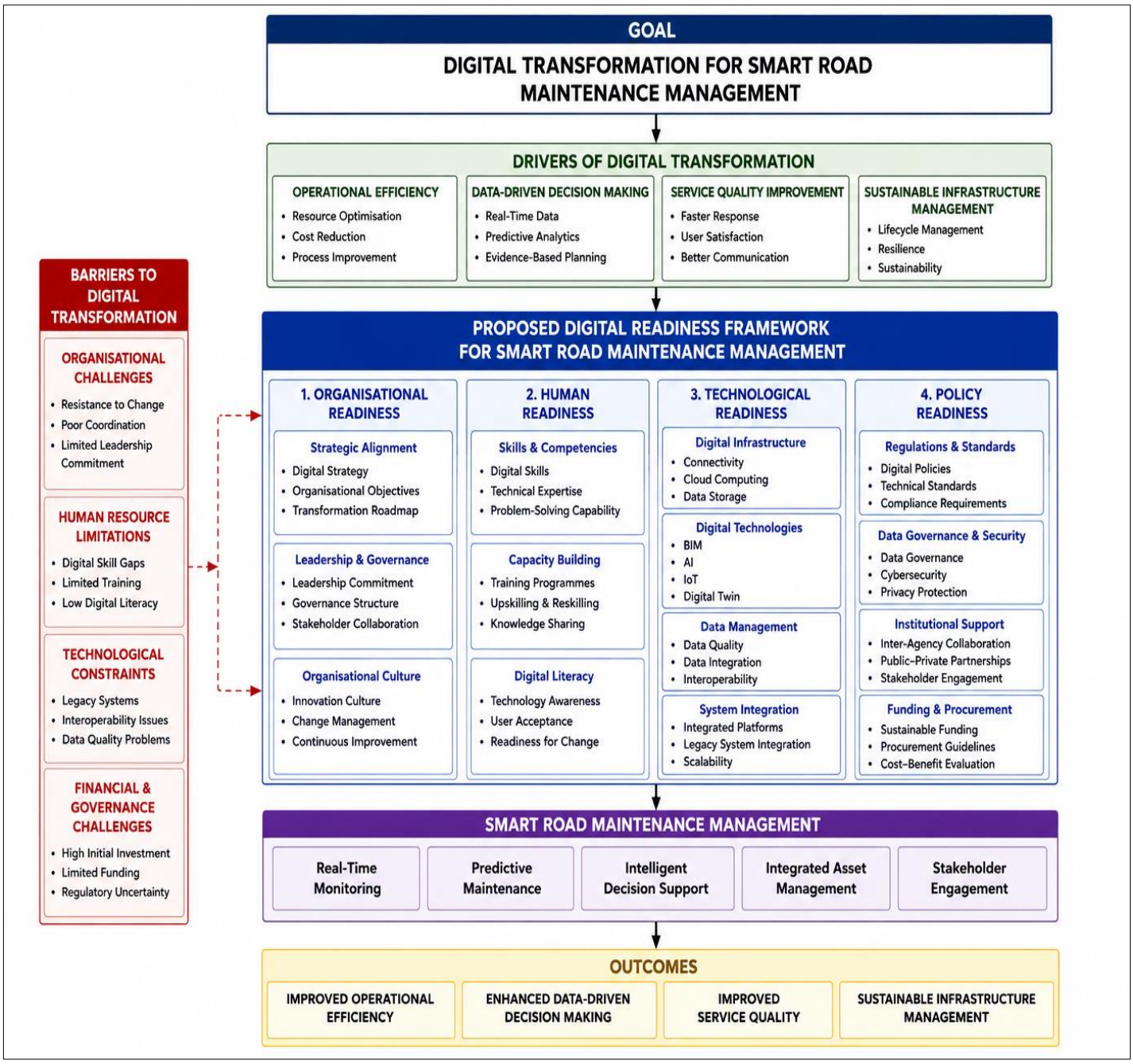

Figure 1. Proposed Digital Readiness Framework for Smart Road Maintenance Management

Critical Discussion

The relative importance of each readiness dimension may vary depending on the organisational and institutional context of road maintenance agencies. In developed countries, organisations often possess relatively mature digital infrastructure and technical capabilities, making policy alignment, data governance, and system interoperability more critical factors for successful digital transformation. In contrast, road agencies in developing countries frequently encounter limitations related to funding availability, workforce competencies, and digital infrastructure readiness, which may hinder the adoption of advanced technologies. Therefore, while the proposed framework highlights four interrelated readiness dimensions, their relative significance may differ across implementation contexts. This suggests that road agencies should prioritise readiness dimensions according to their organisational capabilities, resource availability, and institutional environment rather than adopting a uniform digital transformation strategy.

Implications for Road Maintenance Agencies

The results of the research have numerous practical implications for road maintenance organisations that want to undergo the process of digital transformation. First, it should be understood that digital transformation is not only about implementing new technologies; there should be readiness from both organisational and human perspectives. Before implementing innovative approaches and new technologies, including BIM, IoT, AI and digital twins, the organisations need to have a well-defined strategy, effective management tools, better collaboration with stakeholders, and improved skills. In this case, the suggested digital readiness framework can be used by the road maintenance organisations as an instrument for conducting a strategic assessment.

The suggested framework is also an effective tool for policymakers, infrastructure operators, and technology providers who are involved in the management of road maintenance activities. Policymakers can take advantage of the proposed framework and design appropriate regulatory tools, standardized data governance practices, and funding mechanisms that will enable the digital transformation within the field of road infrastructure. The managers of infrastructure companies can focus their efforts on building up their digital capacities as well as investing in digital infrastructure and personnel development. Moreover, technology providers can make sure that their digital solutions fit the needs of road agencies in terms of digital readiness.

Future Directions

Going forward, digital transformation efforts aimed at improving road maintenance management should focus on advancing technology, interoperability, and integrated digital ecosystems for intelligent, predictive, and sustainable infrastructure management. Technologies like AI, IoT, digital twins, predictive analytics, and maintenance platforms are some of the emerging technologies that have the potential to greatly help with infrastructure management [26], [28], [30]. Technological advancement notwithstanding, digital transformation would require the implementation of robust governance frameworks, supportive policies, workforce training, collaboration with other stakeholders, and good data governance among other factors [27], [29]. It is therefore important that future studies investigate affordable and scalable digital solutions, sustainable financing models, workforce reskilling, and multi-disciplinary approaches to digital transformation that consider all the aspects.

CONCLUSION

The concept of digital transformation has gained recognition as an important strategy for enhancing the efficiency, effectiveness, and sustainability of road maintenance management. Four main drivers of digital transformation have been identified in this research, such as operational efficiency, data-driven decision making, quality of service improvement, and sustainable infrastructure management. In addition to this, organisational, human resource-related, technological, and financial/governance issues have been identified as critical barriers to achieving effective digital transformation initiatives. Drawing from the findings of the literature review conducted, a Digital Readiness Framework for Smart Road Maintenance Management has been developed consisting of four important dimensions that include organisational readiness, human readiness, technological readiness, and policy readiness. The framework offers an overall picture of what is needed to achieve a successful implementation of digital transformation initiatives. Improving these dimensions is likely to help road

maintenance agencies strengthen their capabilities to use digital technologies to make more effective decisions about maintenance, optimise resources, and achieve better outcomes in terms of sustainability of infrastructure management.

Ethical Considerations

This study is a narrative review based exclusively on published literature and secondary sources. Therefore, ethical approval was not required as no human participants, animals, or primary data collection were involved in the study.

Conflict Of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Data Availability Statement

The data supporting the findings of this study are derived from publicly available published literature and sources cited within the manuscript. No new datasets were generated or analysed during the current study.

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