Smart urban pavement management system

by

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SYSTÈME INTELLIGENT DE GESTION DES CHAUSSÉES URBAINES

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RÉSUMÉ

Une ville intelligente et durable (VI) utilise les technologies de l'information et de la communication (ICTs) pour répondre aux demandes de ses citoyens et de sa main-d'œuvre, aujourd'hui et à l'avenir. À mesure que l'urbanisation s'accélère, de nouveaux problèmes apparaissent, tels que les inégalités sociales, la congestion routière, les défis de la gestion des infrastructures urbaines qui vieillissent et les problèmes connexes. En raison des outils disponibles, une meilleure gestion des infrastructures urbaines peut être atteinte. En effet, un des paramètres critiques d'une VI est sa gestion des infrastructures en particulier routières. Un système de gestion des routes (PMS) fait ainsi partie intégrante d'une VI pour optimiser les ressources physiques ou financières. Un PMS collecte, stocke, analyse et modélise les données sur l'état des routes et peut être amélioré en ajoutant de nouvelles technologies d'acquisition et d'analyse. C'est dans cet esprit que cette thèse développe une approche intégrée de la gestion intelligente de la voirie urbaine. Cette approche est basée sur la détection automatisée des fissures (ACD) et l'évaluation automatique des besoins d'entretien et de réhabilitation (MRNA). L'approche fournit également un outil de visualisation critique d'aide aux décideurs élus représentant les parties prenantes ou à tout citoyen pour apprécier l'état actuel et les besoins futurs. Cette thèse adapte une approche conventionnelle pour l'ACD basée sur l'IoT, notamment le LiDAR et la caméra RGB, qui intègre un modèle de prédiction de fissuration par intelligence artificielle (AI) et un outil de visualisation pour apprécier les conséquences de différentes stratégies d'entretien et de réhabilitation (M&R) sur les futures stratégies de gestion urbaine.

Cette thèse comprend trois articles. Une nouvelle architecture est présentée dans le premier article sur la gestion des infrastructures urbaines. À l'aide de cette architecture, tous les aspects d'un système innovant de gestion des infrastructures urbaines (SUIMS) sont évalués, et des modèles et projections de leur état futur sont établis. Le premier document fournit également une évaluation détaillée des besoins actuels et futurs du SUIMS sur la base de méthodologies innovantes, notamment le cadre du jumeau numérique (DT). Dans le deuxième article, un capteur LiDAR mobile 3D accompagné d'une caméra RGB, à titre de capteurs IoT urbains, consacrés à la saisie de données géométriques de la chaussée et des fissures, téléchargées sur une plate-forme SIG et analysées avec MEPDG pour identifier les besoins de M&R. Sur la base des résultats du PMS, un modèle CityEngine est établi pour répondre aux besoins des agents de l'administration municipale et les priorités des parties prenantes. Le troisième article établit le potentiel de la réalité augmentée (AR) dans une approche PMS intelligente et fournit les besoins en matière de M&R basées sur l'état présent et futur de chaque section de route. Le résultat final de la visualisation est livré dans l'article sous forme d'expérience AR, unique à la thèse. En utilisant le moteur de jeu et les textures intégrées, cet article fournit un produit d'analyse de données dynamique et développe un système d'aide à la décision (DSS) pour l'analyse en temps réel pour les utilisateurs finaux.

Cette thèse conclut que les chercheurs peuvent, selon les besoins, recourir à de nombreux outils différents afin de concevoir et de mettre en œuvre un PMS efficace, et évoluer vers une ville intelligente et durable. Le concept d'une ville intelligente et durable repose ainsi sur une collaboration étroite entre toutes les parties distinctes de chaque système de gestion des infrastructures urbaines. De plus, cette thèse apporte des perspectives pour les recherches futures, le développement de la méthode proposée et son application.

Mots clés: Ville intelligente, GIS, système de gestion des chaussées, réalité augmentée.

SMART URBAN PAVEMENT MANAGEMENT SYSTEM

Maryam MORADI

ABSTRACT

A Smart Sustainable City (SSC) uses information and communication technologies (ICTs) to meet the demands of its citizens and workforce both now and in the future. As urbanization accelerates, new problems emerge, such as social inequality, road congestion, urban infrastructure management concerns, and related issues. Due to the proven capabilities of new data acquisition and analysis tools, urban infrastructure management can be improved. One of the critical parameters of an SSC is its road infrastructure management. A Pavement Management System (PMS) is an integral element of an SSC to optimize natural or financial resources. PMS collects, stores, analyzes, and models road condition data and could be enhanced by adding some of the latest technologies. It is in this context that this thesis develops an integrated system for intelligent urban road management. This system is based on automated crack detection (ACD), and automatic maintenance, and rehabilitation need assessment (MRNA). The system also provides a critical supporting visualization tool for the elected decision-makers representing the stakeholders or any citizen to appreciate the present condition and future needs. This thesis adapts a conventional system for ACD based on IoT, notably light detection and ranging (LiDAR) and RGB camera, which integrates artificial intelligence (AI) a cracking prediction model, and a visualization tool to appreciate the consequences of different maintenance and rehabilitation (M&R) strategies on the future condition of the road network.

This thesis includes three papers. A novel architecture on urban infrastructure management is presented in the first paper. Using this architecture, all aspects of an innovative urban infrastructure management system (SUIMS) are assessed, and models and projections of the future road conditions are analyzed. The first paper also provides a detailed assessment of the SUIMS's present and future needs based on innovative methodologies, including the digital twin (DT) framework. In the second paper, a 3D mobile LiDAR sensor accompanied by an RGB camera as urban IoT sensors, are used to capture geometrical pavement data and cracks, uploaded on a GIS platform, and analyzed with the mechanistic-empirical pavement design guide (MEPDG) to identify M&R needs. Based on the PMS results, the CityEngine model, which is based on city administration officers, municipalities, and stakeholders' priorities, is provided. The third paper establishes the potential of an additional feature, augmented reality (AR), in an intelligent PMS to illustrate M&R recommendations based on each road section's present and future conditions. The final visualization result is delivered in the paper as an AR experience, which is unique to this thesis. Using the game engine and embedded textures, this paper provides a dynamic data analysis product and develops a Decision Support System (DSS) for real-time analysis for the end users.

This thesis concludes that researchers need many different modules to design and implement an efficient PMS to move toward an SSC. The concept of SSC is meaningless without a tight collaboration between all distinctive parts of each urban infrastructure management system. Additionally, this thesis attempts to provide an outlook for future research.

Keywords: Smart sustainable city, GIS, pavement management system, Augmented Reality

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LIST OF ABREVIATIONS

VI	Ville Intelligente
SSC	Smart Sustainable City
ICT	Information and Communication Technologies
PMS	Pavement Management System
AI	Artificial Intelligence
AR	Augmented Reality
IoT	Internet of Things
CIM	City Information Modeling
GIS	Geographic Information Systems
DT	Digital Twin
SUIMS	Smart Urban Infrastructure Management System
MEPDG	Mechanistic-Empirical Pavement Design Guide
VR	Virtual Reality
ML	Machine Learning
O&M	Operation and Maintenance
M&R	Maintenance and Rehabilitation
IRI	International Roughness Index
AEC	Architecture, Engineering, and Construction
DSS	Decision Support System
CNN	Convolutional Neural Network
BIM	Building Information Modeling

ACD	Automatic Crack Detection
R-CNN	Region Convolution Neural Networks
PCI	Pavement Condition Index

LIST OF MEASUREMENT UNITS

S	Second (time unit)
m	Meter (length unit)
Mm	Millimeter (length unit)
Cm	Centimeter (length unit)
Km/h	Kilometre per hour (speed unit)
Hz	Hertz (frequency unit)
O	Degree (angular unit)

INTRODUCTION

The world population is now centered in urban areas. About seven out of ten people will reside in cities by 2050 (Nations, 16 May 2018). Cities are the primary emitter of greenhouse gases and energy use worldwide. Socioeconomic inequity, poor and unsafe transportation systems, water impurity, and health problems have increased with rapid urbanization. Governments and municipalities can use information and communication technologies (ICTs) to measure, comprehend and take intelligent and sustainable decisions in smarter cities. A smarter city enables the efficient operation of urban services and procedures while guaranteeing that through the appropriate use of ICTs, it serves the commercial, ecological, economic, and cultural demands of current and future generations. A schema of an ICT infrastructure in a smart city is displayed in Figure 0.1.

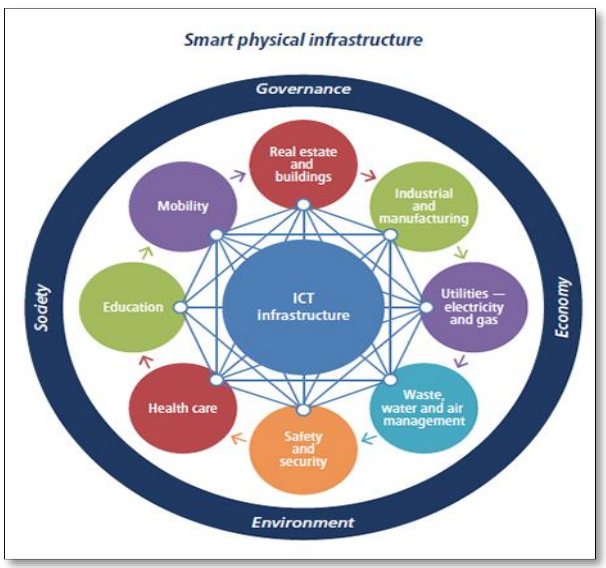

Figure 1.1 A Schema of ICT infrastructure[1]

[1] Source: Abdelfatteh, H., Sanae El, H., Abdelhak, A., & Asmaa El, H. (2016). The Role of Communication Technologies in Building Future Smart Cities. In S. Ivan Nunes Da & F. Rogerio Andrade (Eds.), *Smart Cities Technologies* (pp. Ch. 4). IntechOpen. https://doi.org/10.5772/64732

Continuously assessing infrastructure condition and analyzing needs is key to making cities more efficient. Using intelligent city concepts, policy and decision-makers can make better decisions in real-time (Matheus et al., 2020). The old-fashioned method of performing such a task manually would be extremely time-consuming and expensive (Ersöz, 2016). Managing urban infrastructure in financial and technological aspects is more efficient using ICTs (as illustrated in Figure 0.2) making the smart city concept a reality.

Figure 1.2 Different modules of an intelligent city urban infrastructure[1]

The interior structure of a house is analogous to urban infrastructure: The framework is the building's fundamental structural support; just as urban infrastructure is a city's basic structural

[1] Source: Thiez, P. L. (2018, October). *Smart city: Energy challenges facing sustainable cities*.

foundation. Roads, vehicles, people, and even informational circulation are as crucial to a city as blood circulation in the human body, therefore managing urban infrastructure and maintaining it in good condition is essential for each municipality.

Monitoring the condition of urban infrastructure, including distress is essential because it provides the ability to act in almost real-time in response to data received (Paepae et al., 2021). Some tragedies can be avoided by analyzing the real-time changes in condition or characteristics, with proactive decision-making algorithms (Matheus et al., 2020). City information modelling (CIM) and geographic information systems (GIS) have been used in several initiatives to improve the management of urban infrastructure.

CIM is equivalent to Building Information Modelling (BIM) to manage cities. BIM has been used in the construction industry for several years. Since the 1990s, it has been the standard for modelling infrastructures (Wildenauer, 2020). Through the use of these technology models, infrastructure condition and needs can be simulated throughout the entire lifecycle. A BIM model provides geometric and semantic information about the modelled infrastructure in 3D.

CIM is a set of symbols representing urban elements in three dimensions. It is also due to GIS 3D's expansion, which now includes many levels and sizes of views, a design toolkit, and a database of 3D elements and their relationships (Xia et al., 2022). CIM adoption can improve urban management effectiveness since it addresses "the total effectiveness of the entire network system" (De Amorim, 2015). The success of CIM is dependent on the creation of a distinctive database to which each of the decision-makers associated to each infrastructure has accessibility. CIM gives urban managers the information they need to make informed decisions and administer the system (Falcão & Beirão, 2020).

On the other hand, a GIS enables city managers to position, manage, visualize, analyze, and save spatial data (Deng et al., 2016b; Mignard & Nicolle, 2014). Access to real-world infrastructures at their locations is enabled by GIS technology. As a result, modelling an infrastructure based on the actual position of its components is possible. On the other hand, unlike CIM, it does not permit in-depth indoor information.

GIS use geospatial reasoning to help transform geographical data into valuable ideas and actions, allowing the engineer or analyst to improve people's lives and build more sustainable cities. The ability of GIS to highlight a city's current needs is one of the reasons why it is crucial for urban management (Нгуен & Нгуен, 2021). Geospatial data from satellite imaging, aerial photography, and remote sensors can provide users with an accurate overview of the terrain and infrastructure. GIS's value rests in its ability to combine enormous volumes of data to balance conflicting goals and resolve challenging issues.

Urban managers can view more data thanks to GIS technology. They track changes over time and predict the effects on the environment. All key stakeholders can be shown how changes will affect the annual city budget plans using GIS, enabling them to make more informed decisions (Tomlinson, 2007). For instance, GIS users can assess the expected effects of various development plans by viewing the current infrastructure conditions in each location. These developments are affected by the emerging concept of the Internet of Things (IoT) in GIS applications.

A network of sensors and infrastructure working together to improve citizens' living conditions in urban areas are known as "IoT sensors in a smart city" (Sharma et al., 2021). These engagements are enhanced when urban design and management include ICTs. IoT makes it possible for natural or virtual things to communicate. Therefore, if these objects are present in the same network or service environment, they can speak with one another (Bajaj et al., 2017; Isikdag, 2015). IoT is a disruptive technology because it allows for active communication between various objects, creating a wealth of information to project tendencies, learn and proactively act. The IoT paradigm is a practical means of integrating different technologies due to its broad networking, distributed computing, and automatic service identification. There are numerous IoT applications developed in intelligent cities (Alam, 2021; Hassan et al., 2021). Cities benefit from IoT sensors to monitor and control the flow of people, commodities, and services. They can be implemented on existing infrastructure. To provide new services in this context, communication networks must be easily expandable and changeable (Bonafini et al., 2019).

The IoT includes three layers (Qian et al., 2018): the application layer, the network layer, and the perception layer. Web-connected devices that provide sensing, detection and gathering capabilities as part of the perception layer communicate and share data with other devices. Sensors, cameras, RFIDs, and GPSs are the technologies used in the perception layer. The network layer moves data between the perception and application layers in terms of device, network, and application constraints. Depending on the capabilities of the connection parties, IoT systems combine short-range network communication protocols like Bluetooth and ZigBee to transmit data from perception devices to a local hub. Depending on the application, Internet platforms such as Wi-Fi, 2G, 3G, 4G, and PLC can transfer long data distances (Talari et al., 2017). The followings are examples of critical urban infrastructure which are needed to get more intelligent in the context of a smart city:

- Roads and Transportation systems
- Sanitation
- Availability of water
- Disposal of waste
- Telecommunications

Due to the importance of roads in managing intelligent urban infrastructure, pavement management is gaining more reputation in urban infrastructure studies. Distresses in the pavement significantly affect driving comfort, vehicle running costs, and road safety (Best et al., 2017). Poor pavement design, high traffic volumes, and environmental factors, including water action and temperature changes, are the leading causes of pavement distress. Tools for detecting pavement distress would help gather data on degrading pavement, describe roadways' condition, and identify the causes of pavement deterioration. To choose the best maintenance and rehabilitation (M&R) intervention and address the issue instead of simply treating the symptoms, which will accelerate the degradation of the pavement, it is necessary to diagnose the reasons for pavement deterioration (Blaauw et al., 2022).

Numerous inspection techniques for pavement distress identification and categorization have been developed. Both automated inspection and manual examination can be used to classify these techniques (Zhang et al., 2022). Pavement distresses detected automatically with specialized tools. Patches, potholes, and cracks are detected using cameras, for instance. Three-dimensional sensors can see nearly all distresses better than two-dimensional ones (McNerney et al., 2022). To find pavement distresses, additional sensors are also used. Examples include using an accelerometer, microphone, sonar, and pressure sensor (Balestrieri et al., 2021; Martinelli et al., 2022). These sensors can only detect a limited range of distresses in any case.

Because of several drawbacks of popular techniques for identifying pavement distresses that affect the effectiveness, dependability, and cost of a pavement management system (PMS); scientists are continually working to build a pavement distress detecting technique that is effective, trustworthy, and affordable (Kheradmandi & Mehranfar, 2022).

Thanks to the capabilities of IoT, which would help access the data required for a PMS, data will be generated and analyzed. This data will theoretically be available and used in real time. GIS can now more intelligently observe and examine all facets of urban road management and repair processes (Bi et al., 2021). Urban planning and first responder transportation planning are only two examples of the many uses for three-dimensional representations. It is significantly simpler to understand what they see when three-dimensional modeling is merged with virtual reality (VR) or augmented reality (AR). The user is immersed in a synthetic environment when using VR. Another viewpoint is AR, which overlays the user's actual world with digitally created virtual things (Schmalstieg & Hollerer, 2016). While the first approach enables individuals to examine experiences in a setting other than reality, the second extends validity with richer knowledge and potential for responsible, practical application.

VR involves creating a digital replica of the physical world. By mixing the real (a 3D representation of the city based on geographic data) and the unreal (a 3D model of a proposed structure) information, VR helps people understand what is conceivable (Bouloukakis et al., 2019). To visualize how the proposed project will appear in real life, the building model can be put in a 3D urban setting. The unique aspect of AR is that it entails overlaying a digital image on a photograph of an actual environment (Hořejší et al., 2020). In recent years, VR and AR have grown more widely used and pervasive in daily lives than just academic studies. In AR, virtual objects that appear in the exact location as actual space are described as an addition to real space. At the same time, VR provides an artificial or simulated environment in which a person feels like they are in the same area as real space (Makino & Yamamoto, 2019).

AR/VR integration gives up plenty of possibilities for more intelligent infrastructure maintenance management applications. It is essential to reveal the hidden core knowledge of the infrastructure's component elements to properly understand user tasks and provide better feedback to the system and users. Information hidden in a component can include its cost, the history of its maintenance, and settings.

We may anticipate that integrating the earlier technologies will result in significant advancements in infrastructure management (Carneiro et al., 2018). Although finding a study or work that included all these technologies is impossible, multiple reported attempts have been made to combine various CIM, GIS, IoT, and AR/VR configurations. Integrating the earlier technologies makes it possible to collect and analyze new data types that may be available and useable anywhere in real-time. As a result, it can now more intelligently monitor each stage of the processes involved in managing and maintaining urban infrastructure. Additionally, such integration results in significant advancements that support the development of cities that are more energy-efficient, resilient, and sustainable (Carneiro et al., 2018).

Some recent studies are summarized in Table 1, which lists the technologies used. Even if there is still much to be discovered, the change in basic assumptions has become well-known for a tendency toward merging technologies. The ones that deal with monitoring infrastructures by giving users access to internal and external parameters to help them make decisions are the most pertinent in this field of research. In table 0.1, columns indicate with “X” which technologies were employed in each study.

Table 1.1 A brief history of the integration of different technologies

Related Work	**BIM**	**CIM**	**GIS**	**IoT**	**AR/VR**
H.Xia, Z.Liu et al. (Xia et al., 2022)	X	X	X		
F.Xue, L.Wu et al. (Xue et al., 2021)	X	X			
A. Borrmann, T. H. Kolbe, A. Donaubauer et al. (Borrmann et al., 2015)	X		X		
B. Wang and Y. Tian (Wang & Tian, 2021)		X	X	X	
Y. Deng, J. Cheng, and C. Anumba (Deng et al., 2016a)	X		X		
Y. Deng, J. Cheng and C. Anumba (Deng et al., 2016b)	X		X		
L. Marek, M. Campbell, M. Epton et al. (Marek et al., 2016)	X		X		
S. Yamamura, L. Fan, and Y. Suzuki (Yamamura et al., 2017)	X		X		
L. Bottaccioli, A. Aliberti, F. Ugliotti et al. (Bottaccioli et al., 2017)	X		X	X	
R. Zhong, Y. Peng, F. Xue, et al. (Zhong et al., 2017)	X		X	X	
M. Breunig, A. Borrmann, E. Rank, et al. (Breunig et al., 2017)	X		X		X
E. Patti, A. Mollame, D. Erba et al. (Patti et al., 2017)				X	X
G. Luchetti, A. Mancini, M. Sturari et al. (Luchetti et al., 2017)			X	X	X

Gathering and analyzing a massive amount of data on the condition and characteristics of urban road infrastructure maintenance is necessary to monitor and maintain them. A GIS is appropriate to organize this data because it is spatial. Several factors make it challenging to access these data at present, such as the fact that most data are still stored on paper, databases are outdated, data reliability may be questionable, and trying to manage a few existing documents and create new ones is time intensive. Ground inspections are expensive and require human resources. As a result, it is needed to increase efficiency, which helps manage and maintain road infrastructure and avoid wasting millions of dollars annually because of poor road infrastructure maintenance actions. Therefore, an integration of IoT, CIM, and AR technologies into a GIS framework will be needed to provide the best M&R actions for every PMS framework of a smart urban infrastructure management system (SUIMS).

The problem defined earlier is addressed in this study by evaluating a low-cost pavement distress detection method based on 2D images and IoT sensors. By incorporating onboard self-driving car sensors, we anticipate this system will be more practical. In the future, self-driving cars will likely be extensively used for assessing road conditions with their onboard technologies, which may streamline pavement data collection, reduce associated costs, collect more data, and enhance the pavement inspection process in the long run. As a result, detecting pavement distress using sensors added to self-driving cars will not require expensive, specialized equipment for pavement assessment.

Self-driving cars utilize various sensing technologies to map their surroundings, including light detection and ranging (LiDAR) (Ortega et al., 2021), radio detection and ranging (RADAR) (Pereira et al., 2020), cameras, and ultrasonic sensors (MJ Chin et al., 2019).

This study uses 3D LiDAR and 2D RGB cameras, the two primary visual sensing systems used in self-driving cars. Then, the GIS and CIM are used in the analysis stages of the designed model to make the M&R decision-making paradigm. The final visualized result of the thesis is presented based on an AR experience, and the capabilities of the produced AR experience in comparison with the previous PMS results are provided.

The following of this thesis includes five chapters. The first chapter discusses objectives and research methodology, while the second chapter reviews the literature broadly. Chapters three, four, and five are three papers extracted during this Ph.D. thesis accordingly. Finally, the thesis conclusion is presented at the end of the document.

CHAPTER 1

RESEARCH QUESTIONS, OBJECTIVES, AND RESEARCH METHODOLOGY

1.1 Research questions

Based on a thorough review of the available scientific documentation, an integrated framework in the field of SUIMS, including applications profiting from artificial intelligence (AI) capabilities, is missing. With increasing migration and population growth in metropolitan areas and the increasing cost of providing and maintaining infrastructure in good condition, managing urban infrastructure within a smart, sustainable city (SSC) becomes necessary to do more with less money. To develop a system to manage the data, analysis, and visualization of such a digital twin (DT), in this thesis, looking for appropriate answers to the following questions are investigated:

- By combining IoT, GIS, CIM, and AR, is it possible to improve the monitoring and management of urban infrastructure through SSCs and make pavement monitoring and condition assessment more efficient and cheaper?
- How can the suggested pavement assessment monitoring system overcome the limitations of the sensors, such as the RGB camera and 3D LiDAR?
- How do visualization technologies contribute to urban infrastructure management, and what is being added to the current infrastructure management systems by applying innovative visualization platforms like AR?

Answering these questions will help develop a management system using data, analysis, and visualization in a predefined framework. Considering the widespread domain of urban infrastructure and various kinds of data, analysis, and visualization, it is decided to establish the research on a specific type of infrastructure known as city pavements to find more precise answers.

1.2 Research scope and limitations

The research scope is on urban infrastructure, particularly pavement management. In the context of metropolitan areas, this research relies on monitoring the pavement surface condition and particularly crack detection.

In terms of data, while traffic volume and distribution data, pavement characteristics and properties, pavement's spatial coordinates, and some other attribute data of the study area are essential parameters, the thesis considers them as attribute data in the PMS design phase.

The security, privacy, and interoperability challenges associated with sensors like RGB cameras and 3D LiDAR are significant. IoT technology can offer outstanding improvements to smart PMS when integrated with CIM and GIS. Despite the maturity of technologies like CIM and GIS, IoT is still in its infancy. As a result, the heterogeneity of IoT sensors makes road maintenance programs challenging.

The convergence of GIS and AR technology is making the AR experience more complex. At present, AR geolocation systems face limitations in accurately locating virtual objects due to being in the early stages of development. There is also a possibility that one infrastructure could be located next to another unintentionally. As a result of these issues, AR environments offer a poor user experience. This means all spatial analysis should be completed before entering an AR environment. Data conversion into 3D information in an AR experience is made difficult by these limitations, making the process more time-consuming and therefore more expensive.

Since there is no similar quantitative analysis in the research scope, the validity of the research is based on its qualitative aspects. The validation mechanism which is applied is a triangulation method.

1.3 Research contributions

This thesis provides theoretical contributions related to the research questions as follows based on the definition of the conceptual framework for intelligent infrastructure management and its application to the published crack automated detection system. The extension in this thesis contributes to simulating future M&R needs in the context of SUIMS, city councils, stakeholders' needs, and their visualization requirements.

As a result of the complex structure and non-uniformity, along with the presence of artifacts and noise, the automatic detection of pavement distress from remote sensing imagery is a promising but challenging task. Stereovision imaging, LiDAR, and terrestrial laser scanning can now be used to collect pavement condition data; however, these systems are expensive, require special equipment, and cannot be applied to any other surface. Sensor systems with such potential are not able to take advantage of their efficiency and effectiveness as a result. Sensor data collection obstacles in this thesis were overcome by combining 3D LiDAR data with RGB camera data.

Research is currently underway in AR technology due to its ability to use existing 3D models and CIM data in smart PMS. A major focus of this thesis, however, has been on visually confirming the required information for pavement management through visualization during the construction phase, where engineers and stakeholders can share viewings during the design phase. AR should therefore be applied during each phase of pavement management with more research being needed. On-site implementation of CIM has faced challenges during the most extended period of a road maintenance system's lifecycle. The reason for this is that information required for CIM during the design, construction and visualization is different, and the reproduced information is vast, so identifying the required CIM data for PMS and interfacing with other systems is difficult. The proposed AR-experienced smart PMS demonstrated faster and easier access to information compared with existing traditional PMS.

Based on the historical records of engineering scientific research, each Ph.D. thesis requires three concepts to broadly view its contribution (Baptista et al., 2015). Figure 1.1 displays these three terms and their relationship.

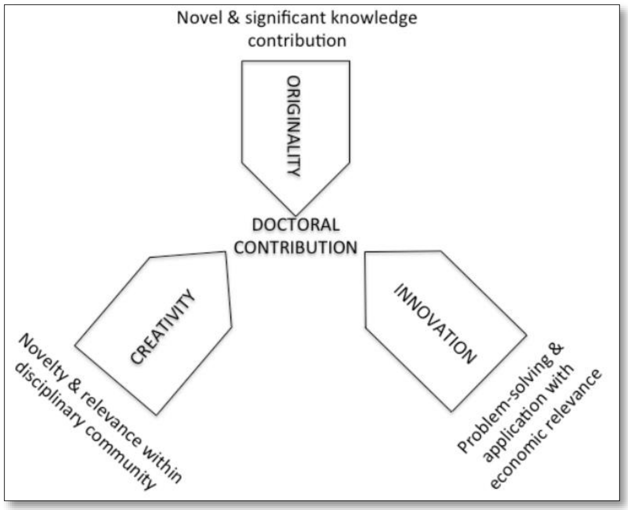

Figure 1.1 A Ph.D. thesis contribution[1]

Originality is not only related to an outcome or product but also to the overall process of producing an outcome. To tackle the term “originality,” this thesis elaborates on why integrating recent technological advancements fulfills the current needs of an urban infrastructure management system.

According to the definition of creativity, it is "the ability to make, do, or become something new and valuable concerning other researchers as well as ourselves" (Baptista et al., 2015). This thesis proves that the full expression of the potential of an urban management system is feasible after considering the capabilities of the designed system and every single component of it.

Innovations of all kinds begin with a creative endeavor, and the attempt must result in work that is not just unique but also helpful. In this thesis, the final output provides the best possible answer to research questions by applying four distinct categories of problem-solving platforms.

[1] Source: Baptista, A., Frick, L., Holley, K., Remmik, M., Tesch, J., & Âkerlind, G. (2015). The Doctorate as an Original Contribution to Knowledge: Considering Relationships between Originality, Creativity, and Innovation. *Frontline Learning Research*, *3*(3), 55-67.

It also discusses how the final visualized result can help city officers and stakeholders prevent wasting millions of dollars annually by providing them with a DT of the city pavements before the implementation phase of each PMS.

Finally, it should be noted that GIS-based PMS is intended to make urban socioeconomic advancements that could contribute to urban management strategies by using recently emerged innovative technologies. Additionally, city organizations should adopt effective leadership styles and become more technologically creative to sustain their success.

1.4 Objectives

This thesis aims to develop and test a comprehensive framework for managing urban infrastructure, emphasizing city pavements using SSC technologies. The specific research objectives are as follows:

1. Enhance the effectiveness of road management practices by developing integrated tools for optimizing maintenance and rehabilitation decision-making processes.
2. Establish and validate an autonomous and inexpensive IoT data collection tool to manage urban pavements and overcome the limitations of the current sensor data collection techniques.
3. Explore and determine the pros and cons of the visualization technologies in the designed framework to greatly enhance interaction possibilities, leveraging on-site accessibility to geographical information stored in GIS platforms and services accessible remotely through the smart PMS.

1.5 Research Methodology

A general theoretical framework for a smart urban pavement management system is essential for establishing consistency, supporting decision-making, integrating data and technologies, evaluating performance, and ensuring readiness for future advancements. The followings are the essential components of this framework that this thesis is focusing on to develop the methodology:

1. Data Acquisition and Integration:
   - Collecting relevant data from multiple sources, such as pavement condition surveys, traffic data, weather information, and maintenance records.
   - Integrating data from various stakeholders and sources into a unified system for comprehensive analysis and decision-making.
2. Data Processing and Analytics:
   - Applying data processing techniques to clean, validate, and preprocess collected data.
   - Utilizing advanced analytics, such as CNN algorithms and statistical models, to derive insights and patterns from the data.
   - Conducting data-driven analysis for pavement condition assessment, deterioration prediction, and performance evaluation.
3. Decision Support System:
   - Developing a decision support system that provides actionable insights and recommendations for pavement management.
   - Incorporating optimization techniques to prioritize maintenance and rehabilitation strategies based on budget constraints, traffic flow, and pavement condition priorities.
   - Enabling scenario analysis to evaluate the impact of different interventions on pavement performance and cost-effectiveness.
4. Real-time Monitoring and IoT Integration:
   - Implementing real-time monitoring systems using IoT devices to capture pavement conditions, traffic flow, and environmental data.
   - Integrating real-time data with the management system to enable proactive decision-making and timely intervention.
5. Visualization and User Interface:
   - Developing user-friendly interfaces and visualizations to present the collected data, analysis results, and recommendations.
   - Incorporating GIS and AR capabilities to visualize pavement conditions, maintenance activities, and other relevant spatial information.
   - Providing interactive dashboards and reports for stakeholders to access and interpret the information effectively.

6. Maintenance and Rehabilitation Execution:
   - Translating the recommended maintenance and rehabilitation strategies into actionable plans and schedules.
   - Monitoring the execution of maintenance activities, tracking progress, and updating the management system with the latest information.
   - Integrating asset management practices to optimize resource allocation and maximize the lifespan of pavement assets.
7. Performance Evaluation and Continuous Improvement:
   - Periodically evaluating the performance of the pavement management system using different metrics.
   - Incorporating feedback from stakeholders, maintenance personnel, and users to identify areas for improvement.
   - Continuously updating and enhancing the system based on new data, technological advancements, and lessons learned.

Evaluation of the pavement network's health and needs for maintenance and repair are the two main goals of the designed system. The condition evaluation must be thorough, timely (often annual or biennial), and timely to detect maintenance and rehabilitation needs, particularly preventative maintenance needs. The best practice, timely preventive maintenance for municipal roads, presents the requirements for the condition evaluation for preventive maintenance purposes. Identifying specific pavement flaws, including transverse cracks, and determining their severity and extent are necessary for condition evaluation. The rehabilitation criteria will also be met if the condition evaluation satisfies the preventative maintenance standards.

As a result, and to meet the first objective of this thesis, the research framework identifies each distinctive stage of the proposed methodology, as displayed in Figure 1.2. The following are the preliminary and critical steps in the systematic process in a large-scale SSC.

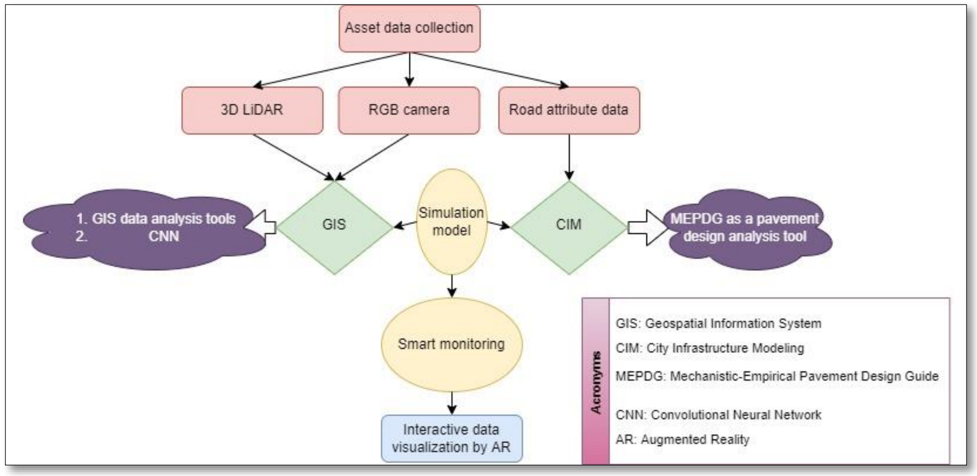

Figure 1.2 The research methodology framework

- *Asset Data Collection*: This stage involves gathering the initial set of asset data, including the geographic positions and attribute data for each road section. This information forms the basis for further analysis and evaluation.
- Making the simulation model: The study integrates two main components: CIM, which encompasses different road section features, cracks, and GIS, which provides decision support system (DSS) capabilities including CNN and analysis tools. The simulation model is developed by combining these elements to facilitate analysis and decision-making.
- *Smart Monitoring*: In this stage, various data sources are utilized to establish connections between different components of the model. The goal is to emphasize significant differences compared to traditional pavement management systems (PMS) and provide reliable real-time data and maintenance work programs. By incorporating smart monitoring techniques, the system can efficiently track and monitor the condition of the pavement network.
- *Interactive Data Visualization*: This step involves creating a digital platform that enables users to process and visualize real-time data interactively. The platform aims to enhance the understanding of scientific issues related to the pavement network and facilitate the generation of unique solutions to improve system management.

Augmented reality (AR) will be utilized to generate interactive visualizations, adding an immersive element to the data exploration process.

Additionally, to address the second objective of the thesis, which involves establishing and validating the data collection tool for urban pavement management, detailed tools and methods are provided in sections 1.5.1 to 1.5.3 accordingly. These sections explain the specific techniques and approaches employed to collect and manage the necessary data.

Finally, to fulfill the third objective of the thesis, which pertains to data visualization, section 1.5.4 provides an interactive explanation of the visualization techniques employed in the research.

1.5.1 Asset data collection

Without a high degree of confidence in asset data, it is impossible to get an accurate picture of the pavement condition and its levels of congestion, which makes informed decision-making more complicated. According to the first preliminary stage, data is taken for each road section within the linked devices and sensors network. Attribute data is also collected and transmitted to the GIS platform. Making decisions between various categories of data quality is a matter of concern.

More high-quality condition data allows urban road agencies to act proactively and reduce reactive maintenance operations. Efficient asset management requires reliable condition data to make cost-effective maintenance decisions and not enormous amounts of useless data.

The IoT can be a key to the sustainable development agenda if the right data is collected at the right time. The IoT would provide sufficient information by allowing various technological devices to collect data and communicate via wireless tools. The IoT would include data on properties or characteristics and data on conditions produced by embedded systems, as well as data from above-road sensors and near-field communication technologies like LiDAR, which may be fixed or mobile. Figure 1.3 shows the LiDAR sensor used in this research. These sensors are applied to collect a wide range of data around the urban environment, including pavement geometrical data.

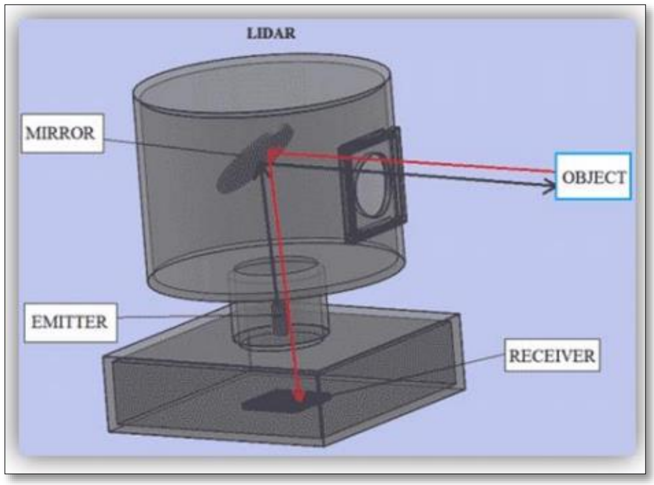

Figure 1.3 Sample of LiDAR sensors

1.5.2 Making the simulation model: Integration of GIS and CIM

Virtual sensors can be mapped to any CIM item (such as road section and their characteristics, water pipes, gas pipes, electrical cables, space, etc.) to send information anytime the status of the CIM object changes (e.g., when a pipe leaks). In this arrangement, the virtual CIM sensors offer information on the state of the utility network, geometric and semantic data, and more. In addition to providing data about the network's semantics and geometries, these virtual sensors also provide information that can be utilized to view the network in a GIS design.

Virtual CIM sensors are digital representations or simulations of physical sensors within a virtual environment. They mimic the functionality and behavior of real-world sensors but exist purely in a digital or simulated form. These virtual sensors are often used in smart city applications to gather data and monitor various aspects of urban environments.

Virtual CIM sensors can be designed to replicate the characteristics of different types of physical sensors, such as cameras, weather stations, traffic detectors, air quality monitors, or noise sensors. They are integrated into the virtual representation of a city or urban area, allowing for data collection and analysis without the need for physical installations or actual sensor infrastructure.

The purpose of virtual CIM sensors is to provide a means to simulate and assess the impact of different sensor configurations, data collection strategies, or scenarios in a digital environment. By leveraging virtual sensors, researchers and urban planners can conduct simulations, optimize sensor placement, test data collection algorithms, and evaluate the effectiveness of various sensor networks in a cost-effective and controlled manner.

Virtual CIM sensors can contribute to the development and validation of smart city solutions by enabling the exploration of different data collection scenarios and helping to optimize sensor deployment strategies. They can also aid in decision-making processes, such as assessing the potential impact of sensor placement on urban monitoring, resource allocation, and infrastructure management.

Sensors connected to IoT nodes offer information on the state of other city-related objects (which will be stored in the GIS). In this design, physical and virtual sensors work in tandem to transfer (geometric/semantic/and state-related) data in the form of messages whenever a city item's state changes, making the decision-making process easy for the city administrations.

An asset management system should help a decision-maker choose the appropriate maintenance schedule to use the resources. The cost of running urban networks is significantly impacted by pavement management which is planned on top of its analysis party. There are many distinct categories of distress along each road section; however, this research is based on the automatic crack detection (ACD) paradigm.

As the first step of the asset management simulation model, the RGB images are extracted from video tracks accompanying the 3D LiDAR. When an image is analyzed, it can detect an object inside it. The object detection process returns both the bounding box and the object category (known as object localization or object classification). Localization and classification tasks are achieved through various methods. The conventional process of constructing region convolutional neural networks (R-CNN) involves three primary steps: (a) proposal of regions, (b) feature extraction, and (c) classification. In the Mask R-CNN paper by He et al. (2017), an additional aspect is introduced, where the boundaries of objects are detected, going beyond the conventional bounding box approach. This particular detection is referred to as instance segmentation. Figure 1.4 provides a visual representation of instance segmentation and its corresponding convolutional layers.

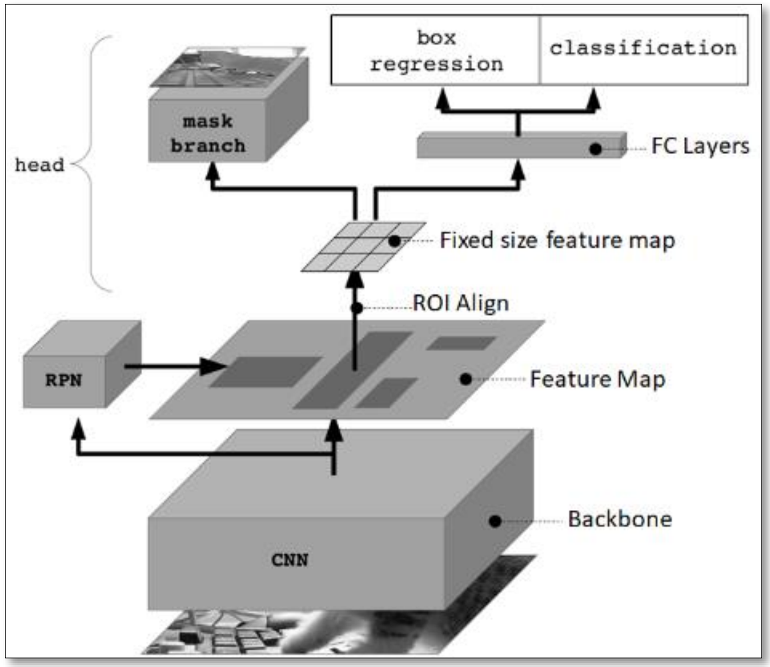

Figure 1.4 Segmentation using Mask R-CNN[1]

1.5.3 Smart Monitoring

The next stage in this thesis will be to figure out how to monitor the integrated model properly while it moves to the SSC paradigm. The design pattern described here is focused on creating a system for integrating data from assets and IoT sensors. The data layer of the architecture is saved in a CIM database or CIM file for network modeling. The spatial requirements of additional urban infrastructure are created and updated using ArcGIS CityEngine. A 3D modeling program called ArcGIS CityEngine allows users to create massive, interactive, and

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[1] Source: Attard, L., Debono, C. J., Valentino, G., Castro, M. D., Masi, A., & Scibile, L. (2019, 23-25 Sept. 2019). Automatic Crack Detection using Mask R-CNN. 2019 11th International Symposium on Image and Signal Processing and Analysis (ISPA),

immersive urban environments in a much shorter time than a traditional modeling tool. To acquire geometric and semantic data on other urban items, a digital city model that can be easily imported into a GIS is employed, focusing on the urban road network.

1.5.4 Interactive Data Visualization

While CIM and GIS can help with performance and profitability in design coordination, they cannot consider the high instability that comes with a system, which is common in construction, especially in large projects. When a state changes at a road section, the message broker will alert an AR message consumer application programming interface (API) connected to a GIS API (such as Google Cardboard, WebXR Device for Chrome, Bing Maps Location Identification, etc.). Then, by integrating with GIS APIs, the AR API can be consulted periodically or used to provide real-time data to the city model. A GIS environment will then display the real-time model. In this case, the user can use a web-based GIS or a desktop GIS in the GIS environment. A use case of AR in a city context is shown in Figure 1.5.

Figure 1.5 AR schema in a smart city[1]

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[1] Source: Bageryan, H. A., Kolchina, O. A., & Lesnichaya, M. A. (2020). Optimization of the Process of Urban Infrastructure Management with Implementation of the Concept of «Smart City». 2020

1.6 Expected results

Hopefully, having access to intelligent pavement management in urban contexts is practical, and this thesis addresses the research questions. It is built on four innovative research technologies: IoT, GIS, CIM, and AR. The design and implementation phase makes a DT with five layers: data gathering, transmission, digital modeling, data/model integration, and application.

LiDAR sensors and RGB cameras are used, called data-gathering sensors in this system, to collect the data. Using an integration of CIM and GIS at the center of the research helps move toward a decision-making platform. Finally, as an interactive way to stay in touch with the users who will benefit from the designed framework, AR is employed to present the results more engagingly.

Going over the various challenges, each specific section of the designed system is being built, and the best solution is recommended. The developed system attempts to apply to the real-world urban environment. It will be used to the available data of Châteauguay City, Québec, Canada.

International Conference Quality Management, Transport and Information Security, Information Technologies (IT&QM&IS),

CHAPTER 2

CRITICAL REVIEW OF THE LITERATURE

2.1 Smart cities regarding IoT technology

Based on the introduction and the importance of considering IoT-based smart cities in great academic action, there is a special issue of a journal that includes 29 papers published by authors from various countries. This special issue on smart cities and IoT and its application to development, implementation, strategies, and policies will provide academic and industry professionals with the opportunity to discuss recent advances, problems, and solutions (Kim et al., 2017).

To move the smart city concept forward, everyday objects are fitted with electronic devices and protocol suites. The hazards presented because of the numerous innovative city programs and projects implemented in recent years have been observed alongside the anticipated advantages. In this descent study, the authors discussed IoT and innovative city trends both now and in the future. Additionally, they went through how smart cities and IoT interact and some factors influencing IoT development and smart city progress. Finally, they discussed specific IoT shortcomings and how to fix them for intelligent cities (Hammi et al., 2018).

Digital technologies and advanced metering have enabled intelligent cities to be supplied with a wide range of electronic devices based on the IoT, making them more intelligent than ever before. An overview of smart cities' concepts, motivations, and applications is provided in a recent study (Arasteh et al., 2016). This survey discusses innovative city elements and characteristics of smart cities and IoT technology. Additionally, the significant difficulties and real-world examples are discussed. Future IoT applications for smart cities are shown in Figure 2.1. It should be mentioned that sensing the environment is not possible without applying IoT sensors.

While smart cities and smart grids share common goals of resource optimization and sustainability, they focus on different aspects of urban development. Smart cities encompass a broader range of urban services and infrastructure, while smart grids specifically target improvements in the electrical power sector. However, there can be synergies between smart cities and smart grids, as both rely on advanced technologies, data sharing, and integration to create more sustainable and efficient urban environments.

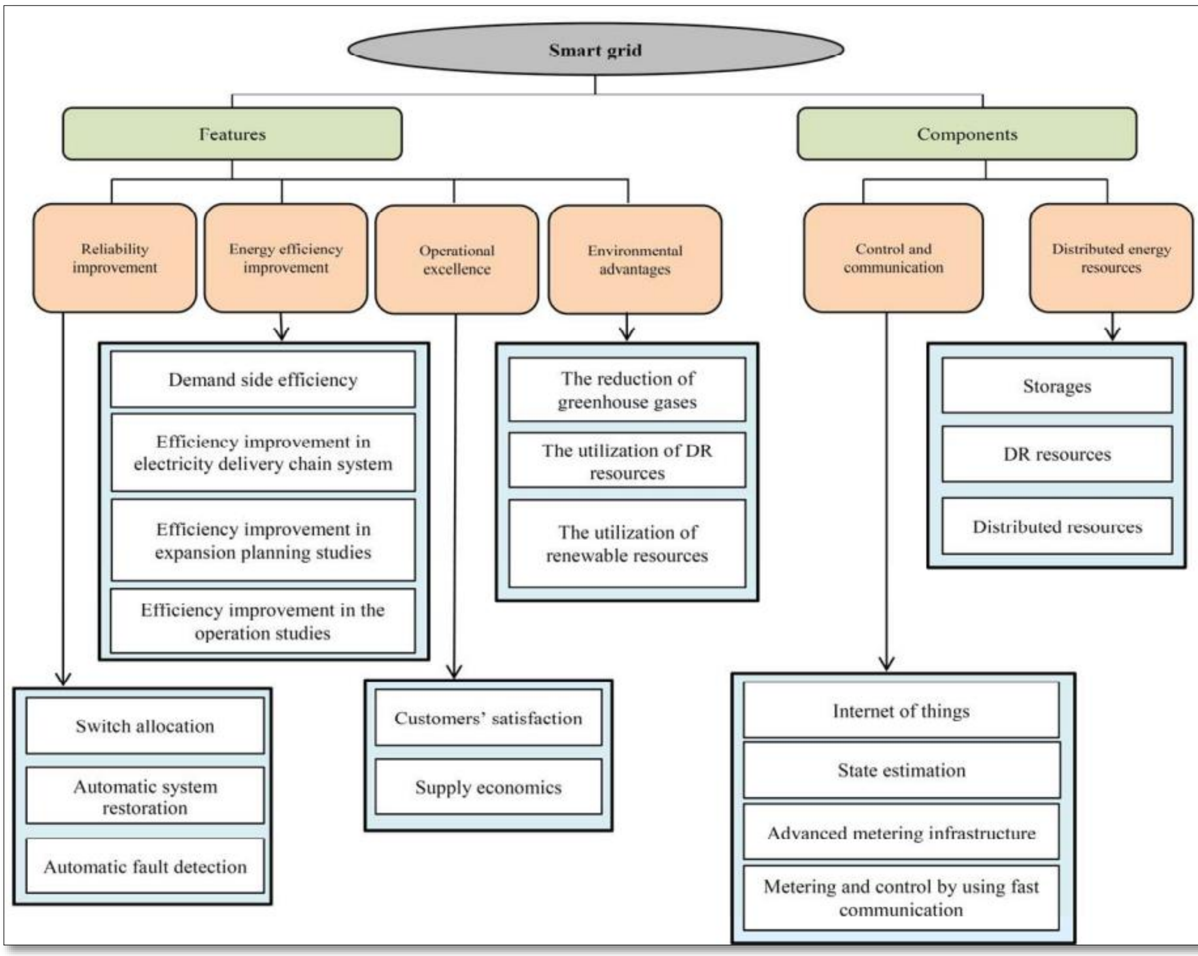

Figure 2.1 The main specifications of smart city components[1]

[1] Source: Arasteh, H., Hosseinnezhad, V., Loia, V., Tommasetti, A., Troisi, O., Shafie-khah, M., & Siano, P. (2016). Iot-based smart cities: A survey. 2016 IEEE 16th international conference on environment and electrical engineering (EEEIC),

An essential and challenging issue that significantly affects the effectiveness of smart city systems is the modeling of sensor data. The technologies and information modeling that can be applied in a smart city context are discussed in a recent study examining how to model sensing and location information to enable smart city growth (Wang, 2015). Due to the role of sensing the urban environment in smart city growth, LiDAR sensors are one of the best examples that can make their sensing role efficient.

There are numerous free and open LiDAR datasets available in addition to ready-to-use 3D city models. National LiDAR datasets from several nations are offered as free and open data with variable levels of coverage and quality. In a recent study (Ortega et al., 2021), the authors outline a workflow for creating level of detail 2 (LoD-2) CityGML compatible city models using publicly available LiDAR point clouds. Footprints are grouped into five categories based on how buildings and rooftop surfaces are approached. An innovative corner-based outline generalization system divides the zones associated with each building in a footprint. Figure 2.2 displays the procedure of making 3D city models using open LiDAR point clouds. LiDAR can be categorized under IoT sensors due to its strength to work in urban areas.

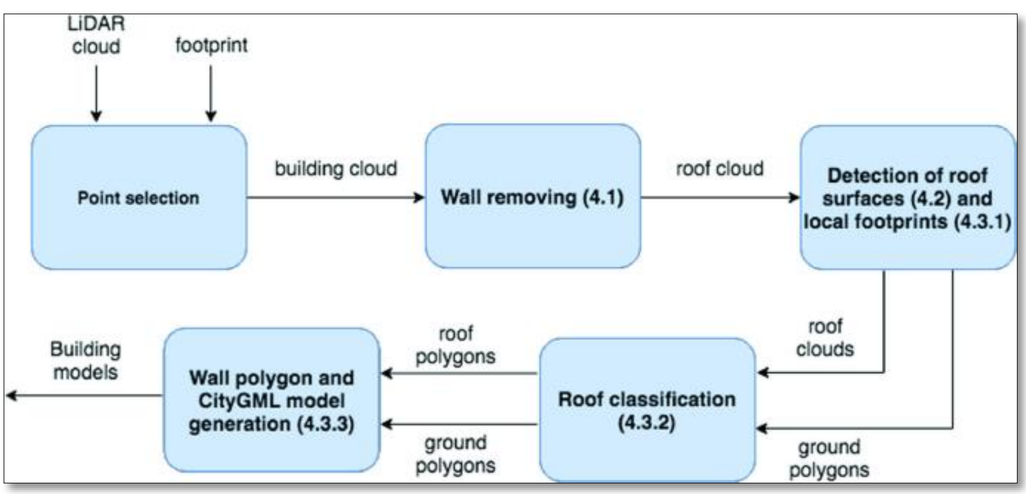

Figure 2.2 Making 3D city models of open LiDAR point clouds[1]

[1] Source : Ortega, S., Santana, J. M., Wendel, J., Trujillo, A., & Murshed, S. M. (2021). Generating 3D City Models from Open LiDAR Point Clouds: Advancing Towards Smart City Applications.

One reason for considering LiDAR as an IoT technology is its ability to provide detailed spatial information about the physical world. By deploying LiDAR sensors in IoT devices, such as autonomous vehicles, drones, or smart infrastructure, it becomes possible to capture precise measurements of objects, landscapes, and structures in real-time. This spatial data can then be processed and analyzed to extract valuable insights for decision-making and automation.

LiDAR in IoT applications can enable:

- Object detection and tracking: LiDAR sensors can detect and track objects with high accuracy, such as vehicles, pedestrians, or obstacles in autonomous vehicles or smart city environments. This information is crucial for collision avoidance, navigation, and optimizing traffic flow.
- Environmental monitoring: LiDAR can be used to monitor environmental conditions, such as air quality, pollution levels, or forest density. By integrating LiDAR with IoT networks, continuous and real-time monitoring of the environment can be achieved, providing valuable data for environmental management and resource planning.
- Infrastructure management: LiDAR can assist in the monitoring and maintenance of infrastructure assets, such as bridges, buildings, or utility networks. By collecting precise 3D measurements, LiDAR can identify structural deformations, assess the integrity of assets, and facilitate predictive maintenance.
- Urban planning and development: LiDAR data can contribute to urban planning by providing accurate and up-to-date information about the urban landscape, including buildings, terrain, and vegetation. This information can support city planners in making informed decisions regarding zoning, infrastructure development, and environmental impact assessments.

In A. Mobasheri (Ed.), *Open Source Geospatial Science for Urban Studies: The Value of Open Geospatial Data* (pp. 97-116). Springer International Publishing. https://doi.org/10.1007/978-3-030-58232-6_6

- Emergency response and disaster management: LiDAR-equipped IoT devices can aid in emergency response and disaster management scenarios. By quickly capturing detailed 3D maps of affected areas, emergency responders can better assess the situation, plan rescue operations, and identify hazards or areas in need of immediate attention.

Integrating LiDAR technology into IoT applications enhances the spatial awareness and capabilities of connected devices, enabling more intelligent and context-aware systems. It expands the range of data that can be collected and analyzed, leading to improved decision-making, efficiency, and sustainability in various domains. Using inexpensive, low-power devices and networking, IoT allows detailed monitoring of a wide range of physical products and settings. IoT for smart cities has attracted increasing attention. Yet, few systematic studies examine big data techniques, such as anomaly detection, to obtain practical insights from authentic IoT data. Denmark's city of Aarhus was used as a case study in a study of a smart environment (Jain & Shah, 2016). Several metrics are used to judge analysis performance, including detection accuracy, the time elapsed, and support vector count. In addition to collecting useful information from data in great quantities, this analysis method can also be used to investigate occurrences more thoroughly. High accuracy can be achieved with machine learning (ML) techniques.

Regarding performance and accuracy, Support Vector Machines (SVM) are considered superior to neural networks in this study. An SVM-based nonlinear classification is more accurate than a linear one. Using only 4 support vectors for anomaly identification, the additional polynomial kernel delivers 95% accuracy (Jain & Shah, 2016). Therefore, the integration of ML and IoT is growing among researchers daily.

Research on IoT and ML methods used in intelligent transportation applications has been published (Zantalis et al., 2019). Various IoT data types and scales have been investigated and reviewed for smart transportation applications, which implies that ML is ideal for assessing this type and scale of data. ML techniques are well-suited for assessing the diverse types and scales of IoT data in smart transportation applications. By leveraging ML algorithms, transportation systems can benefit from data-driven insights, improved efficiency, enhanced safety, and more intelligent decision-making. Despite these features, compared to current IoT and ML applications, intelligent lighting systems and parking applications have much fewer ML applications. The most common IoT for the information technology system's application categories has proven to be route optimization, parking, and disaster prevention/detection. Environmental protection, transportation financing, human safety, traffic control, and time savings are related to smart transportation systems' problems (Zantalis et al., 2019).

Another study (George et al., 2018) discusses traffic circumstances considering IoT technology. It integrates the IoT sensors with the Adaptive Neuro-Fuzzy Inference System (ANFIS). An ANFIS traffic signal controller is created using the Matlab Simulink environment, including inputs such as waiting for time and car density. Utilizing the Arduino UNO and ThingSpeak Platform, the camera captures traffic situations transmitted to the cloud. In the traffic signals, appropriate control signals are sent based on the image assessment using the server's ANFIS controller. Police officers can see traffic conditions in real-time. The use of AR in traffic improves driver safety and comfort as well as allows for autonomous vehicles to be developed. While driving down the road, AR can display crucial information such as speed and navigation path (George et al., 2018).

2.2 Integration of GIS and CIM

The IoT-based smart city's goal is to incorporate the most innovative technology and ideas to improve the field of innovative cities. CIM and GIS are two of the most efficient problem-solving platforms in this context; however, based on the broad review of the recent literature, there is no comprehensive study on the integration of GIS and CIM regarding smart pavement management systems yet. Since numerous aspects of the real world can be represented on a DT basis, it should be defined as one of the leading technologies in GIS and CIM integration.

A DT implies a better reproduction of real resources, forms, and frameworks. DTs use AI, ML, and data analytics to create sophisticated simulation models that gather information from various sources, communicate with physical partners and predict their present and future circumstances (Liu et al., 2021). Regardless, the structures and other framework materials used in the current DT exercises are still in the design and technical development stages. It is still important to talk about when it comes to the life cycle operation and maintenance (O&M) of urban infrastructure.

O&M has received less focus at the longest stage of the resource life cycle. The first step toward successful O&M of buildings and communities would be an organized, straightforward design supported by real-world use cases for organizing a DT. An excellent study demonstrates a carefully thought-out DT system architecture at both the building and city levels (Lu et al., 2020). A DT prototype was constructed using this layout at the University of Cambridge's West Cambridge campus in the United Kingdom. It harmonizes disparate sources of knowledge, upholds efficient knowledge evaluation and questioning, supports decision-making processes in O&M administration, and develops linkages to bridge the gap between a person's interactions with cities and their built environment. The complete DT adoption process at the building and municipal levels is examined in this study, along with the lessons learned and difficulties encountered when putting DTs into practise. Resource management experts, lawmakers, and analysts can utilize this demonstration as a clear manual to illustrate DT questions and to promote the usage and growth of DT (Lu et al., 2020).

Sustainable ecosystems are a fascinating subject that must be considered in DT studies. A recent study examines the relationship between BIM and GIS in sustainable built environments from four perspectives (Cardozo Parada & Marín Fandiño, 2019). Applications are used across the Architecture, Engineering, and Construction (AEC) project life cycle, developments in data transformation, building energy monitoring, and urban management. Based on how each technology dominates the other, three main BIM-GIS integration strategies are categorized: "BIM leads, and GIS supports," "GIS leads and BIM support," and "BIM and GIS are similarly engaged." It emphasizes the significance of advancing data for all aspects of AEC venture planning and increasing semantic models and third-party integration phases. Comprehensive data for building vitality management should be measured and digitized to achieve progress in its orderly synthesis and application to the urban built environment (Lu et al., 2020).

Some recent research depicts the system's primary structure and the technology utilized for the digital modeling of urban systems. Throughout the lifecycle of pertinent systems, asset statistics, operating data, and environmental parameters should be included in the digital modeling of a city. The researchers should also make sure that all the modeling tools are compatible. However, research provides a summary of the most basic city modeling techniques. Various modeling technologies have been developed for urban systems, including CityGML for a 3D virtual model of the city, BIM for construction projects during their life cycle, and GIS for network management (Shahrour et al., 2017). CIM creates a scaled-down version of a city or infrastructure by combining BIM models. This is the same concept as BIM but applied to urban areas and infrastructure.

According to a comparison study, there are substantial differences between semantic enrichment in BIM and CIM in terms of scopes, terminology, methodologies, and scales (Dantas et al., 2019). Recently, a study was conducted to examine the specialized semantic enrichment topic in BIM and CIM. The paper looks at recent advancements in the field and helps readers understand how semantic enrichment has evolved. This paper proposes a six-part conceptual framework for semantic enrichment and explains how it makes sense from a data processing standpoint. The conclusions are based on examining the definitions, techniques, applications, and trends of the two domains' worth of semantic enrichment approach. Due to the expanding availability of data sources, algorithms, and computing power, they invade each other's territory (Xue et al., 2021).

The CIM, considered an advanced public management technique in a DT framework, will be presented by integrating BIM and GIS concepts. Recently, a sewage network management model concentrating on preventive interventions was developed, enabling data-driven decision-making based on the CIM concept. In this research, 1731 wells were used to collect the following information for each sector: depth, location, diameter, pipe type, and flow direction. There are 64 non-precision locations, 316 underground wells, and 1291 visible wells in the sewage system. There were four hidden wells and 56 visible wells in the sewage interceptors. Many sewage network alignments were not determined because of the high number of undiscovered wells (18.5 percent), which should be done as infrastructure maintenance occurs. It was feasible to discover problems and compare the circumstances and characteristics of data infrastructure thanks to constructing a reliable database (Melo et al., 2019).

2.3 Integration of IoT, GIS, and other relevant decision-making technologies in an SSC

Smart Cities' concepts have attracted the industry's attention, thus generating a flurry of research on managing spatial information. There are two critical technologies regarding this subject: GIS and BIM. Although GIS and BIM have been used for many years, their combined application provides a new system that is just beginning. To better understand this recently expanded field, an exciting study examines previous research and relevant application platforms in BIM and GIS integration (Ma & Ren, 2017). As shown in Figure 2.3, an understanding of major studies on the integration of BIM and GIS can be gained based on the charts.

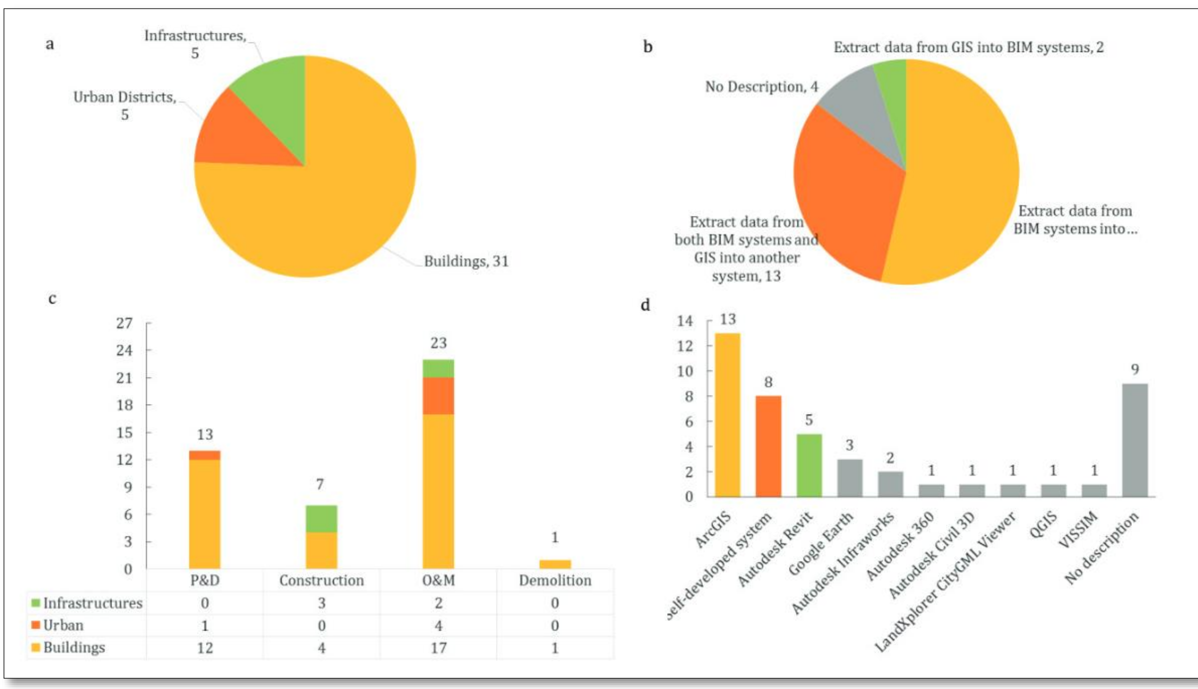

Figure 2.3 (a) Application object distribution; (b) integration pattern distribution; (c) application phase distribution; (d) platform distribution[1]

[1] Source: Ma, Z., & Ren, Y. (2017). Integrated Application of BIM and GIS: An Overview. *Procedia Engineering*, *196*, 1072-1079. https://doi.org/https://doi.org/10.1016/j.proeng.2017.08.064

Another research describes a GIS-BIM collaboration system and its implementation that allows the visualization of resource flows over multi-scale network infrastructures. The design denotes how a software system may link power network components at various scales through graph databases, signal brokers, and web technologies. This technique was proven to be a method of real-time interpreting the flow of utility supplies across the interior/outside interface in a case study focusing on the dynamic visualization of power demand-supply between urban and residential sizes. The graph representation is more flexible and allows for the depiction of resource flows without relying on pre-existing schemas and their overlapped concepts. The integration, modeling, and distribution technique used in this study is depicted in Figure 2.4 (Gilbert et al., 2018).

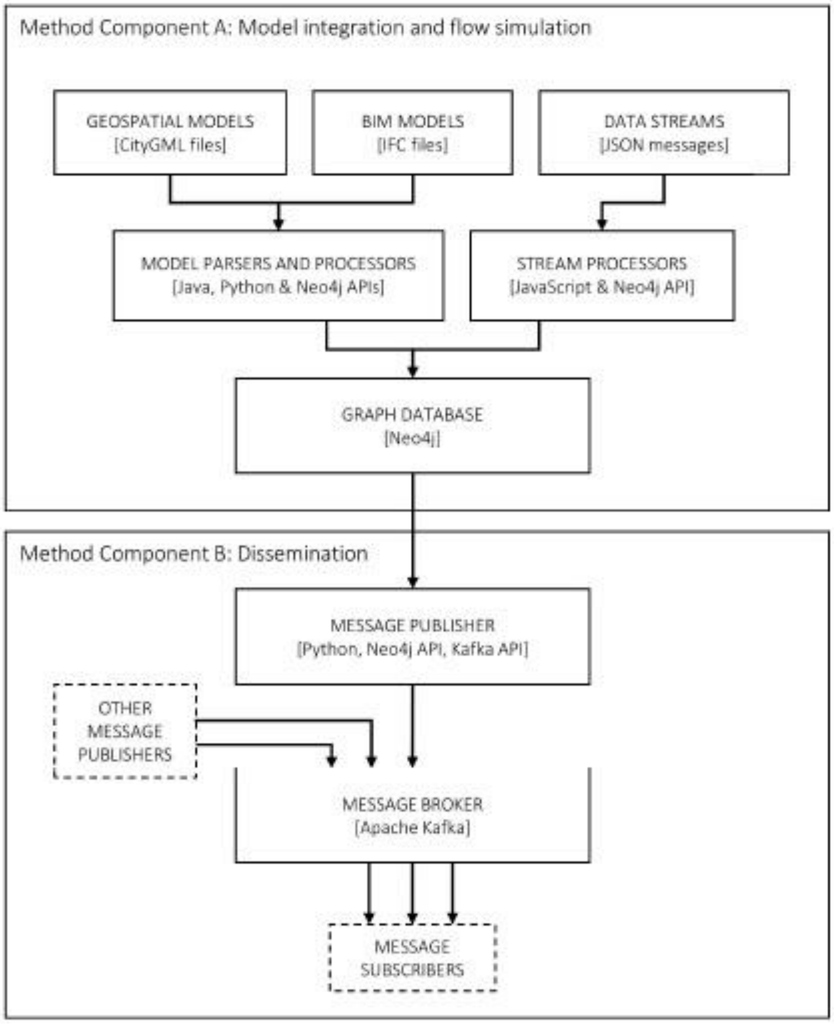

Figure 2.4 Integration, simulation, and dissemination method[1]

Another recent study examines how BIM and GIS may be combined to provide guidelines for intelligent cities and increase their effectiveness. Additionally, it outlines the potential benefits of BIM and GIS integration for upcoming advances in several other fields. The authors

[1] Source: Gilbert, T., Barr, S., James, P., Morley, J., & Ji, Q. (2018). Software systems approach to multi-scale GIS-BIM utility infrastructure network integration and resource flow simulation. *ISPRS International Journal of Geo-Information*, *7*(8), 310.

conclude that two-dimensional data on maps cannot be used to answer managerial challenges regarding vertical development. However, the horizontal and vertical management issues in infrastructure development projects can be efficiently resolved by integrating BIM and GIS. Given that both models offer unique characteristics for data unification, quantitative analysis, technology applications, and city management, their integration provides sustainable support for a smart city (Khaleghi et al., 2022).

The integration of IoT, BIM, and GIS has several advantages that (Isikdag, 2015) published recently:

- *Crowd-Sourced Monitoring*: This system is great for continuing to monitor events and disasters. For example, real-time tracking of a forest fire's spread can be made possible by crowdsourced monitoring or the IoT. Nodes installed in forest structures can determine whether the fire has reached the area by transmitting information on the temperature and gas levels within and outside the building. Many homes might quickly become submerged in water in the case of a tsunami. A cluster of active nodes (near non-flooded structures) may be able to provide vital details on the local floodwater invasion.
- *24/7 Monitoring of the City and Buildings*: Data from this pervasive source would be primarily used in municipal dashboard applications. BIMs and IoT Nodes will provide continuous access to data without interruption in an emergency or disaster. Information from the building model is essential if anybody wants to know the typical CO2 level in the rooms that the fire has not destroyed. The location of emergency response vehicles can be determined using data from IoT nodes, for example.
- *GIS Type Independence*: It is possible to implement the defined architecture with any GIS client, whether a paid desktop GIS, a server-based GIS, or a web GIS. The only requirement on the client-side is the ability to connect to a service consumer API. Building data and sensor data would be gathered and presented in real-time through the loosely coupled structure of the proposed architecture. Regardless of their hardware, operating system, or software, interested parties will be able to access room temperature, humidity levels, the status of building elements (such as window open/closed), the condition of lifts (such as in operation or not), interior oxygen

saturation, and other gas levels. Similar data gathered from municipal objects, such as air pollution, noise levels, UV radiation levels, bus stops, metro stations, and street parking occupancy rates, can be used and easily accessible in real-time.

Another exciting study run by Bottaccioli and his colleagues analyzed the BIM-GIS-IoT connection, presenting a solution that allows for real-time monitoring and simulations of an infrastructure's energy use (Bottaccioli et al., 2017). The authors considered the climatic conditions. The authors created a middleware based on web services to address the heterogeneity-related interoperability problems in IoT sensors. The system's cloud-based software component models and administers the infrastructure. All three types of databases—IoT sensor databases, BIM databases, and GIS databases—are linked. The infrastructure relating to the environment and energy can also be evaluated using the data collected by IoT sensors. Infrastructure management can monitor system performance data such as energy usage, temperature, and efficiency while making real-time decisions.

Power outage is another issue each city may confront in the energy field. A real-time Web Map Service (WMS) can be used by any geo-enabled program to display a web map of the state of current power outages and corresponding macroeconomic losses (Nourjou & Hashemipour, 2017). The geographic web services enable electric businesses to prioritize operations restoration to decrease the fiscal impact of outages. They also provide a real-time evaluation technique for disaster response management and emergency planning in the energy industry. By enabling real-time planning and decision-making, supporting operational decisions, addressing significant issues, and creating innovative and imaginative experiences, it can assist smart electric utilities and intelligent cities in improving the efficacy of recovery operations. The lives saved, the property maintained, and the businesses that continue after a disaster will show that their towns are more resilient. One disadvantage they consider in their approach is using Esri ArcGIS (Nourjou & Hashemipour, 2017). "ArcGIS for Server," an expensive piece of software, is used in the solution. They also need to build a GIS server that is scalable and customizable. Another downside is the use of rudimentary models, although their self-contained computer software can provide a scalable framework for various data analyses. One of these goals may be considered as tackling the environmental issues in a city.

In a late study, the authors provided an IoT-based BIM solution that considered environmental and geographical data (Teizer et al., 2017). Two examples successfully developed a conceptual model for production and operation management. These included BLE beacons, sensor-enhanced personal protective equipment (PPE), BIM, and an IoT platform (Figure 2.5). The technologies' compatibility was effectively validated in simulated lab conditions and under regulated working conditions. According to the study's preliminary findings, real-time project data can be collected and visualized. The validation shows that linked, digital, and intelligent technologies have the potential to be applied in civil and environmental engineering, as well as the construction industry schema.

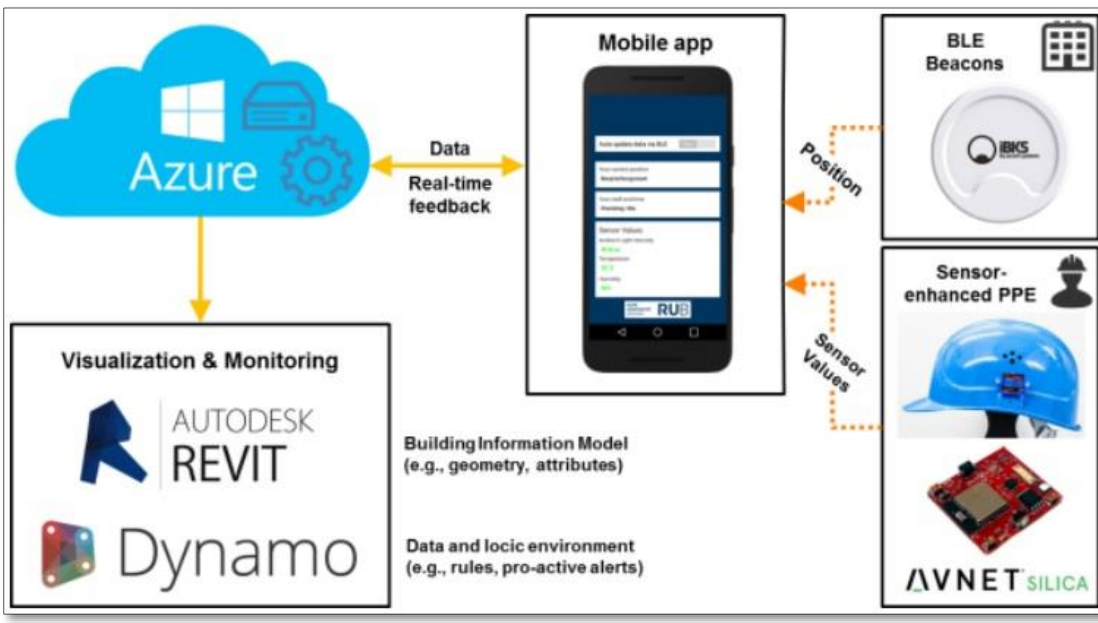

Figure 2.5 IoT for data collection, cloud platform data storage, processing, and communication[1]

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[1] Source: Teizer, J., Wolf, M., Golovina, O., Perschewski, M., Propach, M., Neges, M., & König, M. (2017). Internet of Things (IoT) for integrating environmental and localization data in Building Information Modeling (BIM). ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

The link between IoT and BIM ontologies in the construction industry is essential, which was examined in another study (Baracho et al., 2017). It is shown that in the context of the IoT, an ontology may represent items and their connections. IoT sensors collect and send crucial environmental data, while BIM technology enables 3D modeling of infrastructure using the IoT database. It is concluded that the construction sector may be improved and reinvented by combining BIM, IoT, and ontologies.

Another excellent study showed a BIM-IoT fusion to connect and share all data with other users and add additional features to BIM models, such as budgeting and timelines (Zhong et al., 2017). The system offers the visibility and traceability required to track the project’s status, progress, and expected cost more effectively in real-time. It also incorporates prefabricated construction applications. Data on building progress, resource consumption, and employee assignments are collected via IoT devices. As a result, participants have real-time project updates and may make decisions based on them to improve every citizen’s quality of life.

Finally, a review of the literature in this section specifies a study that assesses citizens' quality of life. Since urban researchers are always looking for the solution to optimum use of the available devices to maximize the citizen's quality of life, active aging indicators and big data were used in a study to boost the quality of life in fixed IoT environments. The study aims to develop a system for objectively monitoring and measuring the quality of life of older people in a stationary IoT and BIM technology environment by using biomarker sensors to determine their active aging status. The authors identified and suggested using biomarker sensors and active aging measures to generate an objective HRQOL composite score in place of the subjectivity of the HRQOL question response. They also employed fixed IoT and BIM to construct a system for objectively measuring, transmitting, and storing biomarker sensor values (Roh & Park, 2017). They conducted a pilot study to examine if there was a link between HRQOL survey results and active aging biomarker readings. Furthermore, all the study's participants were nursing home residents in their senior years.

2.4 Integration of different technologies, including AR/VR, IoT, BIM, and GIS

Smart cities must be developed through the coordination and fusion of numerous technologies and the thorough, flexible, and compelling fusion of all facets of urban planning. The CIM is built on integrating data at multiple spatial scales while paying attention to the access and calculation of enormous real-time big data from the IoT, as seen from the analysis of the fundamental technologies of the CIM. Every one of its three key technologies—BIM, IoT, and GIS—contributes to developing smart cities with a specific set of advantages. They are all closely intertwined and related (Wang & Tian, 2021).

A 3D urban model that the CIM combines with rich BIM semantic data can be used for urban planning, urban project management, and as a database for the government to authorize building permits and control the storage of BIM model files. The management of urban cadastral information has benefited from GIS. Urban cadastral information management has advanced thanks to the creation CIM cadastral database. Recent research has also produced a model for land management that is inclusive and more participatory, in addition to automating the procedure of determining whether buildings comply with building licenses and granting electronic permits in smart cities (Atazadeh et al., 2019; Noardo et al., 2020; Shahi et al., 2019). To evaluate the city and visualize it in a virtual environment, a decent study run suggests a GIS-IoT-WebVR combination (Lv et al., 2016). The system may also perform 3D spatial analysis and visualization of the spatial data process. It also gives GIS and VR users a unified external access interface and access to each model. It can be more efficient to regulate the cities if observing and assessing the city's status in real-time is done. The writers created this study to increase environmental protection, public safety, management, and infrastructure maintenance. Using this strategy, they aimed to create greener environments. They also recommend using WebVR, GIS, and IoT to study and visualize the city in a virtual setting. The technology is also capable of deciphering and analyzing three-dimensional spatial data. It also gives users of GIS and VR access to each model as well as a consistent external access interface. It can better govern the cities if they can track and visualize their current state in real-time. The authors hope to improve environmental legislation, public safety, management, and infrastructure maintenance through this study. Using this method, they wanted to build greener habitats (Lv et al., 2016). Besides the importance of this integration, consistent use of 3D models during the planning of virtual environments is necessary too.

In outdoor AR applications, significantly augmented games set in realistic environments, there are several synergies between the 'world' requirements and geomatics tools and techniques. To provide highly immersive and interactive experiences, AR applications require accurate 3D models of the world. Models of real-world settings can be created with centimeter-accurate accuracy using high-resolution LiDAR scanning for use in AR and situated games; such models can be leveraged by many other applications (Harrap & Daniel, 2009).

The application of integrated technologies in managing crisis, which is a part of urban infrastructure, is crucial, and the visualization usage of AR is essential. Most municipal data visualization applications are currently run on PCs, mobile devices, and other gadgets. The Microsoft HoloLens, an innovative AR gadget, is used to examine a three-dimensional city model of Toronto and numerous forms of city data to benefit from AR innovation. The study covers creating a 3D city model, extracting city data, managing geographic data, and client interaction (Zhang et al., 2018). Figure 2.6 depicts a user interacting with an enhanced 3D city model of Toronto and related city data while wearing a HoloLens.

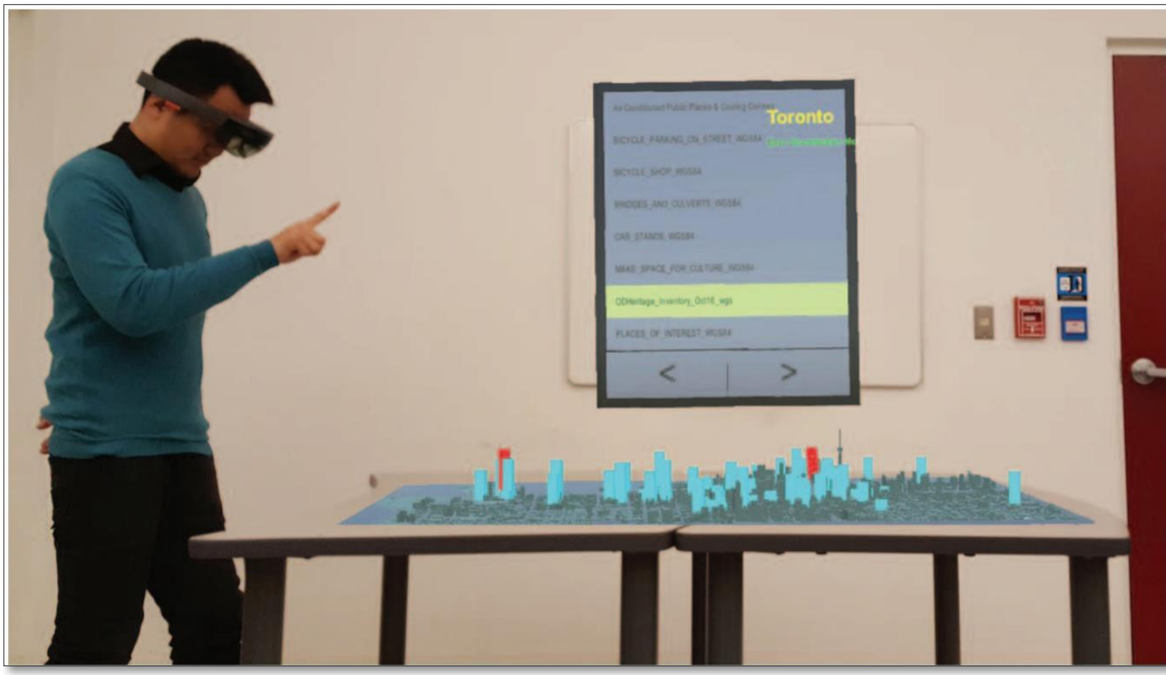

Figure 2.6 A user visualizing and interacting with an augmented Toronto city model and data on real tables with HoloLens[1]

As an example of the role of the integration of different technologies in a city crisis circumstance, here is presented how natural disaster event cycles must be avoided and appropriately controlled by employing technological devices. The advent of embedded and mobile innovative computing systems provides civil protection operators with additional options for managing land and infrastructure. Until now, researchers have primarily concentrated on social media to respond to catastrophes caused by meteorological/hydrogeological phenomena of earthquakes rather than emphasizing the importance of a comprehensive approach. The Whistland platform (Luchetti et al., 2017) combines AR, Crowd-Mapping (CM), social networks, and IoT to make intelligent judgments

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[1] Source: Zhang, L., Chen, S., Dong, H., & El Saddik, A. (2018). Visualizing Toronto city data with Hololens: Using augmented reality for a city model. *IEEE Consumer Electronics Magazine*, *7*(3), 73-80.

about the sequence of events using Web 2.0 and GIS 2.0 technologies and frameworks. A geo-server, an AR smartphone application, and an analytics dashboard make up the Whistland system. The geo-server connects social networks and sensors. The transformation of the user domain into "intelligent sensors" is the abstract concept for the entire spectrum of crisis management. A smartphone application built on an AR engine handles the internet networking integration, using an effective pointer-like method to reduce storage needs while providing qualitative data that sensors cannot. Real-time data, location, and the ability to examine event history using an AR engine enable stakeholders to understand better the state of the resources being watched or monitored. The system has undergone extensive testing in river basin management, where it is crucial to keep an eye on maintenance efforts to keep riverbanks clean—a typical use case in many countries that experience hydrogeological instability. Figure 2.7 shows the mobile application for the suggested model.

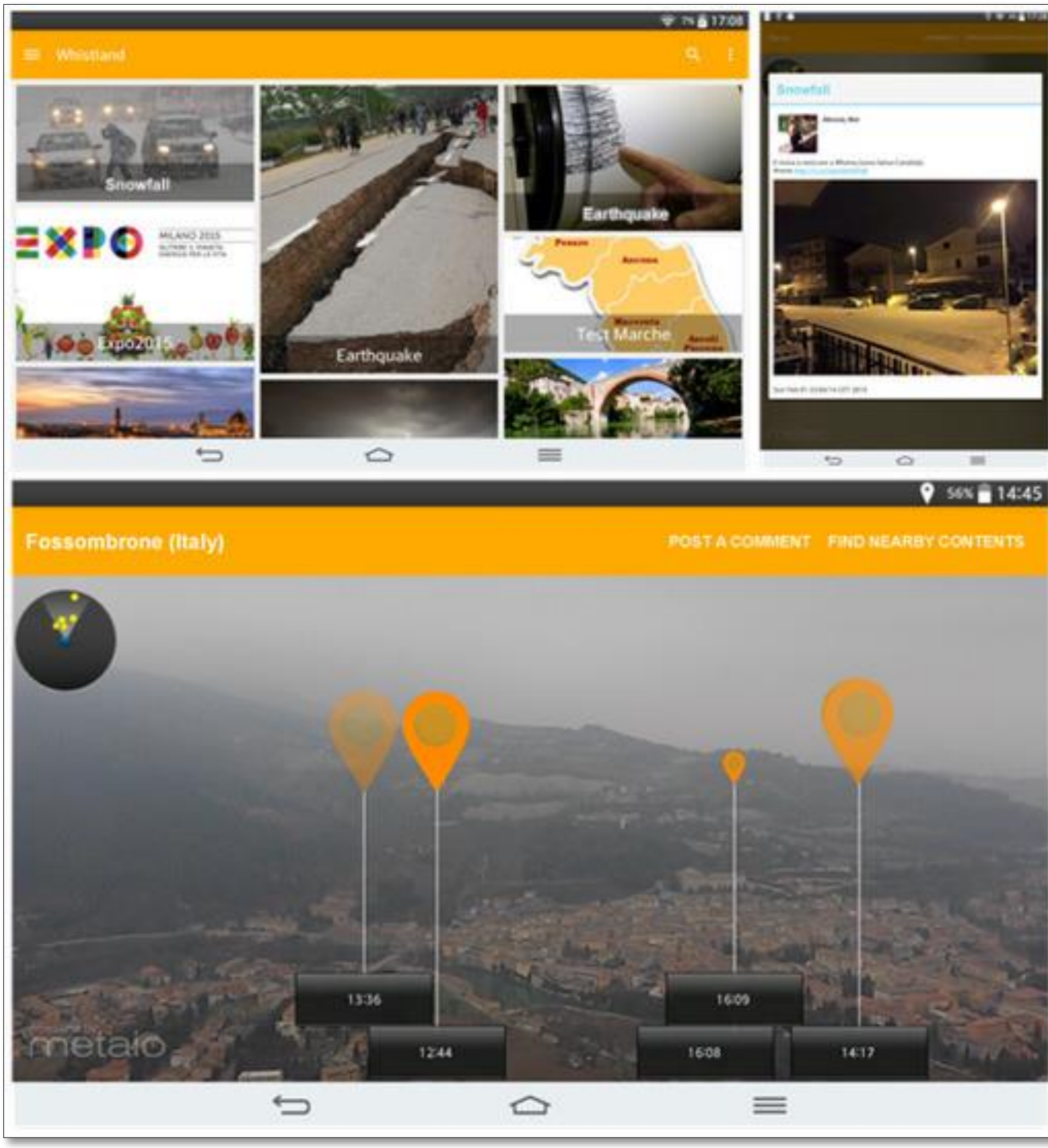

Figure 2.7 Mobile applications in different operating states. Top left: the main menu with most relevant events; Top right: details about a geo-marker; Bottom: example of the overlay of geo-tweets close to the user in AR mode[1]

[1] Source: ibid.

Applying this integration in the building industry could be an exciting topic of discussion. Here is a study that offers a BIM and AR synthesis in the building industry (Wang, Love, et al., 2013). A theoretical schema that integrates BIM and AR has been established for application in the building. Figure 2.8 illustrates the three layers that make up the structure. BIM, context-aware AR tracking, and sensing are interactive. The components of AR visualization are not only for providing visualization but also for flexible planning and crucial context-aware monitoring and sensing. The platform's built-in deployment and intelligence layer allow it to combine BIM and AR to collect and present data on "as-built and as-planned progress," as well as "current and future advancement." AR was used, among other technologies, to monitor processes, link digital and real worlds, track, and control material flows, and reason how different tasks relate. It was also used to visualize designs while they were being made (Wang, Love, et al., 2013). The principal shortage of such a study is the ignorance of environmental data from intelligent building devices.

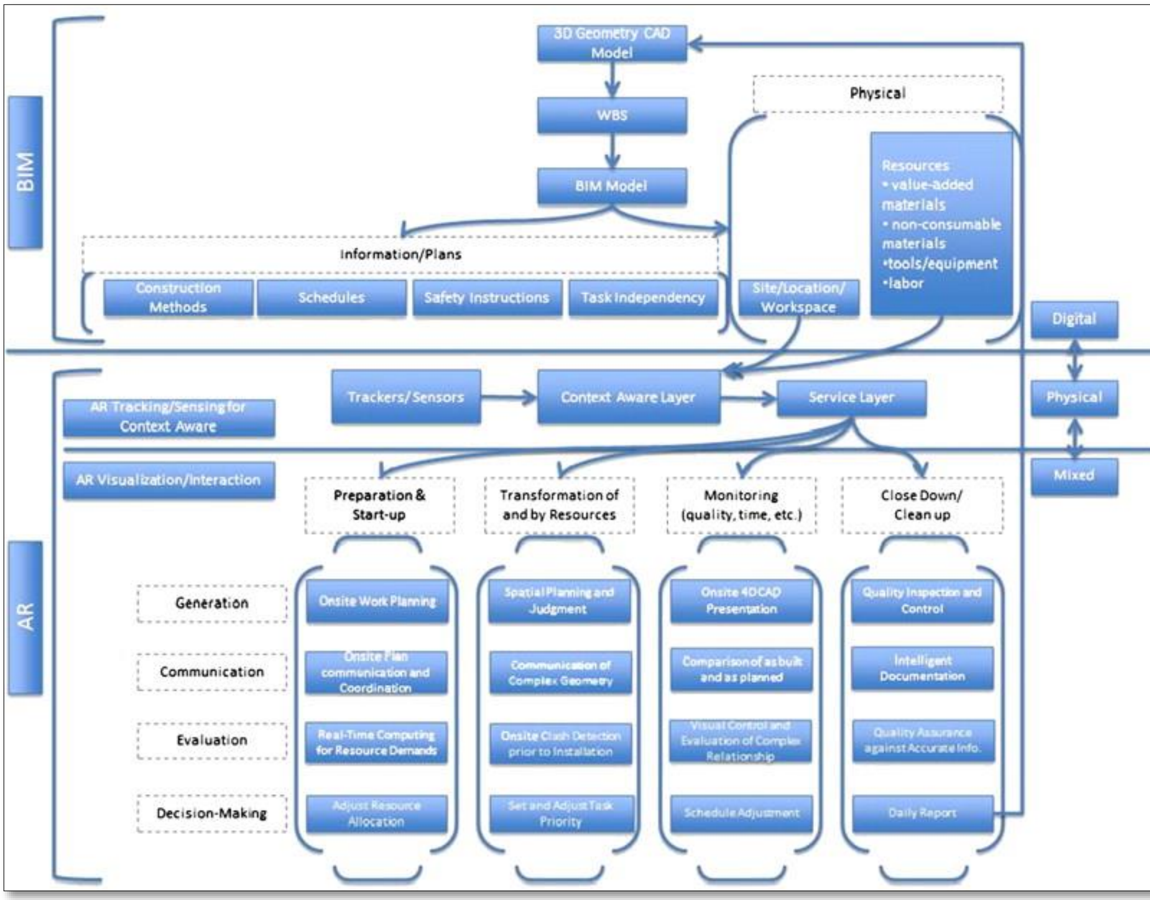

Figure 2.8 Integration of BIM and AR in construction[1]

Environmental data from intelligent building devices can be merged with BIM data (Patti et al., 2017). The Android-based app could deliver AR and VR environments with BIM data and environmental building information. In their research, they recommend combining BIM, IoT, and AR. Users of the system, an Android-based application, may collect BIM-IoT data while walking in an AR world. Using QR codes as markers in the AR recognition system makes it possible to identify which equipment is present in a scene quickly. They also developed a

[1] Source: Wang, X., Love, P. E., Kim, M. J., Park, C.-S., Sing, C.-P., & Hou, L. (2013). A conceptual framework for integrating building information modeling with augmented reality. *Automation in construction*, *34*, 37-44.

middleware layer to address issues with IoT sensor compatibility. BIM models can retrieve and include environmental information like temperature and energy consumption. This connection allows users to leave their computers and have local access to the infrastructure's pieces of information via the AR environment.

Furthermore, the user has a decent understanding of the ecological parameters of the infrastructure to make the urban environment a better place for the next generations. However, there is a lot of work to move toward SSC. One of the examples visible in many cities around the world is the weakness in railway infrastructure. Due to the absolute need for technological advancements in the complex train and subway track infrastructure, the upgrades of old-fashioned railway infrastructure provide difficulties for computer-aided collaboration and multi-scale 3D design in the real world. There are several structural, legal, economic, and environmental considerations.

The representation of cross-domain spatial data sets is a growingly essential task in analyzing energy simulations in the context of smart cities. Because they enable users to examine the results of various models and simulations in the virtual environment at the place of interest, location-based services (LBS) are a helpful addition to the analysis and visualization of such data sets (Santana et al., 2017).

An innovative mobile service that enables users to explore urban models using well-known standards like CityGML at various levels of detail is presented by the authors of a recent study (LoD). It is based on the fields of computer graphics, geographic information systems, and mathematical simulation. In the project's final stage, researchers, urban planners, and technologists will be able to examine urban energy datasets utilizing Virtual Globes, VR, and AR. The last service was developed and tested on the iOS platform using models of the city of Karlsruhe, giving an empirical understanding of the system's performance (Santana et al., 2017).

Using 3D models consistently throughout the planning process improves communication and collaboration among stakeholders, including civil engineers, geologists, and decision-makers. However, another interesting research in which the authors emphasize concepts, discoveries, and experiences made by an interdisciplinary research group combining BIM and 3D GIS expertise from civil engineering informatics and geoinformatics (Breunig et al., 2017). New strategies for stakeholder engagement and modeling, such as creating a collaborative framework and 3D multi-scale modeling, are advised to enhance the digital 3D design of subway lines and other infrastructure. The study's findings and lessons are explored, and a look forward to future research focused on BIM and 3D GIS applications for future cities with an emphasis on environmental issues.

2.5 Conclusion

In conclusion, this literature review has explored various aspects related to smart cities and the integration of emerging technologies such as IoT, CIM, GIS, AR/VR. Through an examination of the existing literature, several key findings and insights have emerged.

Firstly, the review highlights the significant role of IoT technology in the development of smart cities. The utilization of IoT devices and sensors enables efficient data collection, analysis, and decision-making processes, leading to improved urban services, resource management, and citizen engagement.

Secondly, the integration of CIM and GIS has been identified as a powerful approach for urban planning and management. The combination of these technologies facilitates the creation of comprehensive digital representations of cities, incorporating various data sources and enabling advanced spatial analysis, visualization, and simulation.

Furthermore, this literature review emphasizes the importance of integrating IoT, GIS, and other relevant decision-making technologies in the context of smart sustainable cities. By combining these technologies, cities can achieve enhanced environmental sustainability, optimized resource allocation, and improved quality of life for their residents.

Lastly, the integration of additional technologies, such as AR/VR, CIM, and GIS, presents exciting possibilities for smart city development. These technologies enable immersive experiences, enhanced visualization, and efficient city management, contributing to the overall advancement and effectiveness of smart cities.

By synthesizing and analyzing the literature in these areas, this review contributes to a better understanding of the current state-of-the-art in smart city technologies and their integration. It also highlights several research gaps and opportunities for future studies, such as the need for standardized frameworks, data interoperability, privacy and security considerations, and the evaluation of long-term sustainability and societal impacts.

In conclusion, the findings presented in this literature review underline the significance of integrating various technologies in the development of smart cities. This integration holds great potential for improving urban planning, resource management, and the overall well-being of citizens. As the field continues to evolve, further research and practical implementations are required to address the challenges and harness the full benefits of these integrated technologies in creating smart, sustainable, and livable cities.

CHAPTER 3

INTELLIGENT MANAGEMENT ARCHITECTURE OF URBAN INFRASTRUCTURE

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This chapter presents the paper submitted to the Scintia Iranica journal. This paper addresses the first research question. It discusses the requirements to assess and analyze the present condition of intelligent urban infrastructure and simultaneously model and project their future state. It contributes to the design of a smart administration of urban road infrastructure by utilizing IoT and AI and assisting critical stakeholders in overcoming existing obstacles. Additionally, it has achieved the paper's initial goal by identifying and examining the precise tools needed to research and create an urban management system within a DT framework to comprehend the system's behavior. It gives a broad picture of the entire system and illustrates how variations in system components could impact various levels. This paper discusses the necessity for creating SUIMS in terms of either technological or analytical tools based on the review of the literature and the results obtained. The assumption and study of pavement management in a city setting serve as a case study of urban infrastructure.

Abstract

Smart cities are becoming more critical in today's world. One of the most dominant fundamentals in the structure of a smart city is urban infrastructure management. There are numerous infrastructures in a city that need to be considered in this system. In this paper, an innovative architecture for urban infrastructure management is designed. This architecture includes all aspects of managing urban infrastructure: assessment and analysis of their present condition, modeling, and projection of their future state, and their present and future detailed needs assessment based on an innovative methodology whereby the reason for the deterioration is identified and relevant tests arranged. The technically justified needs assessment is followed by an economic evaluation whereby an internal rate of return (IRR) is attributed to each technically justified intervention. Conducting such a considerable volume of data in a city requires a detailed and step-by-step hierarchy based on peer-viewed technologies like AI and IoT. Focusing on DT implementations and the need to bring all DTs' benefits into everyday life, designing a SUIMS that incorporates these technologies to move a smart city will be discussed. In this study, three subsections will form the SUIMS: data preparation, information extraction, and policymaking based on information integration. This paper concludes that SUIMS has several advantages over traditional administrative frameworks.

Keywords: Smart city, Urban infrastructure, Internet of Things, Digital Twin.

3.1 Introduction

In today's world, smart cities are moving from concept to reality. To make cities more intelligent, city officials need to constantly monitor their infrastructure, measure and analyze the relevant information, and update the performance of real-time models to improve managing policies and decision-making (Bageryan et al., 2020). This system can be carried out physically using conventional measuring techniques and post-analysis, which is time-consuming and expensive. Monitoring infrastructure conditions, determining the causes of deterioration, and adapting the decision-making system to avoid solutions that do not meet expectations is critical because it allows us to make real-time informed decisions based on the data collected (Carneiro et al., 2018). This paper makes the case that real-time data and design based on performance is a preferred system.

In terms of managing urban infrastructure, the assessment and analysis of the present condition, the modeling and projection of future requirements, and present and future needs assessment would benefit from a system that is continuously and automatically improving, thanks to the IoT, AI, and the multitude of readily available software for civil engineers (Chinnici et al., 2020). In addition, a DT framework will bring easy access to all the relevant information on a 3D visual platform which provides the type of infrastructure, the location, the dimensions, the materials, and finally, all the properties and characteristics of urban infrastructure. The DT is a virtual model that improves the understanding in real-time alongside its physical partner (Lu et al., 2020). An urban framework DT system is illustrated in Figure 3.1. This paper focuses on the urban road network, which is one of the essential elements in an urban framework DT system. Urban pavements significantly impact the city's successful movement and economic progress. Road infrastructure has been key to economic prosperity in the last hundred years. In a recent study, the authors believe that road infrastructure will be better managed and, therefore, the quality and life cycle cost-optimized due to the DT architecture (Lu et al., 2020).

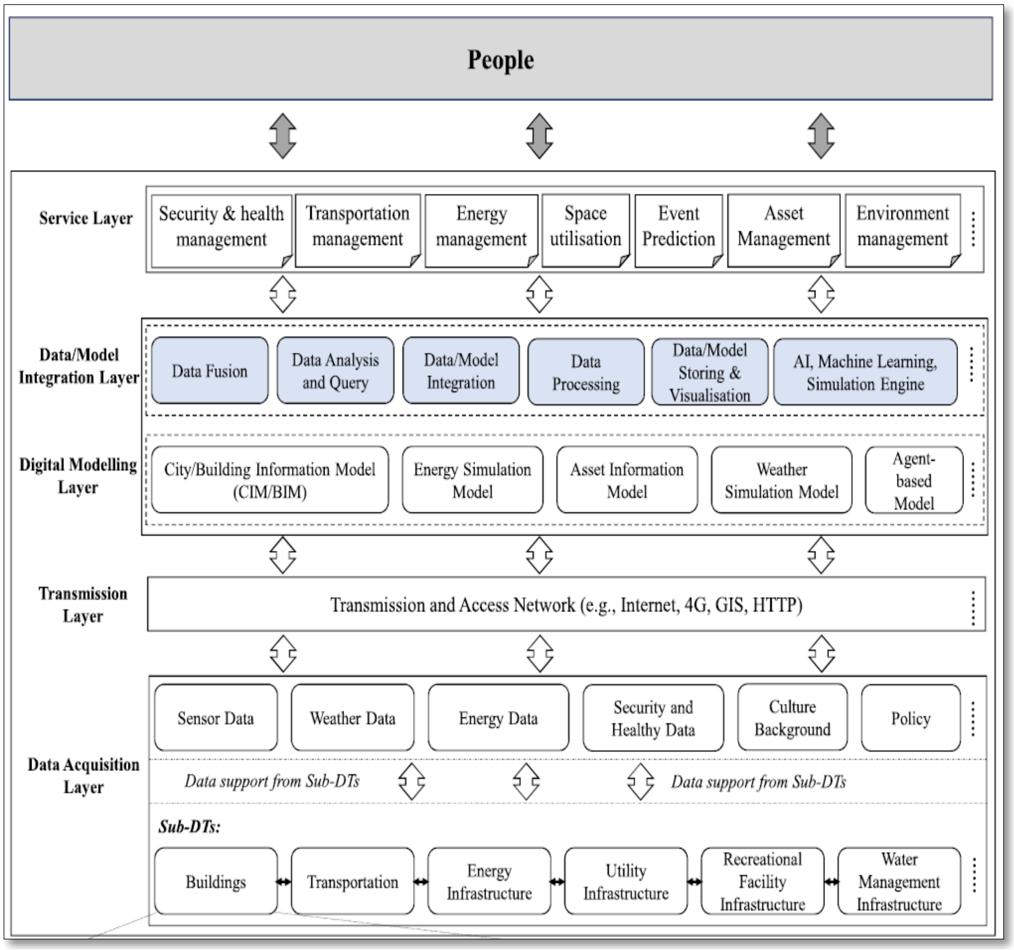

Figure 3.1 DT architecture of city infrastructure[1]

Due to the importance of the road network, built in an urban environment that grows exponentially, the management of disaggregated streets becomes an objective for city administrative agencies (Buyvol et al., 2020). The absence of an appropriate road management system reduces citizens' quality of life. It leads to congestion or waste of citizens' travel times

[1] Source: Lu, Q., Parlikad, A. K., Woodall, P., Ranasinghe, G. D., Xie, X., Liang, Z., Konstantinou, E., Heaton, J., & Schooling, J. (2020). Developing a Digital Twin at Building and City Levels: A Case Study of West Cambridge Campus. *Journal of Management in Engineering-ASCE*, *36*(3).

and a squander of cash and assets. Poor infrastructure management processes will result in road degradation, such as potholes and cracks, hindering sustainable development. Therefore, city managers are constantly looking to resolve this issue with more yearly funding (Smith, 2020). A substantial amount of money is invested yearly in urban infrastructure worldwide (France-Mensah et al., 2018). Evaluating the city street's overall condition is essential to monitor and preserving valuable assets (Yu et al., 2021). Such an evaluation is predicated on manual visual assessment shown in Annex J of MCC Roads Development and Implementation Guidelines (Yohannes Abebe, 2014). These surveys are necessary to predict the condition of every single infrastructure in a city, such as pavements that have been done recently in the City of Châteauguay (Québec province, Canada), and table 3.1 refers to it briefly (L. Capotosto, 2021).

Table 3.1 Distresses surveyed in recent research in Châteauguay[1]

Name of the street	Length (m)	Width (m)	Functional class	Quality	Transversal cracks	Mesh cracks	Shore cracks	Longitudinal cracks	Ripples / Ruts	potholes
Major Street	38	7	Residential	90%	8	Mild. Opening 5mm or less	10%	Mild. Opening 5mm or less	----	----
Scott street	282	6	Residential	60%	3	Mild. Opening 5mm or less	20%	Mild. Opening 5mm or less	40%	Mild. Opening 5mm or less

Based on table 3-1, the street functional classes, materials, buried infrastructures underneath, and the complexity of the whole street framework make the road condition data analysis problematic (Souliman et al., 2014). The street condition evaluation is based entirely on the information and involvement of technicians, which shifts among different individuals. Considering that any decision is subject to the quality of the data, the latter must be reliable. Poor data can lead to bad decisions that can be costly to the city and road users due to poorly timed periodic maintenance. Concurrently, some streets have been kept up repeatedly,

[1] Source: Capotosto, L. (2021). *Développement d'une plateforme intégrée pour l'optimisation de la conception de la réhabilitation des chaussées* École de technologie supérieure]. Montreal.

although the condition is acceptable and vice-versa (Radopoulou et al., 2016). Identifying the cause of deterioration is equally critical if a proper diagnosis is made to determine the technically justified intervention. To resolve these issues, the most vital parameter is having access to reliable urban road data.

The road maintenance backlog exacerbated by the increasing urban construction results in remarkably high occupied density and increasing demand for cars and other services may be addressed within IoT and digitalization. These technologies can help (1) constant monitoring of critical infrastructure decision-makers and (2) illustration of such in a convenient representation to help locate, visualize, and appreciate the status of the infrastructure. This monitoring and illustration may help municipal officials manage infrastructure economically without depending on human bias regarding the subjective condition evaluation at a given time compared to reliable, continuously monitored data. There are five advantages to this proposed architecture (Tarabay, 2020):

1. Real-time data as opposed to outdated data.
2. Continuous monitoring in time and space versus discrete one-time or sampled data.
3. Reliable data if the system has been appropriately validated and regularly calibrated.
4. Data is automatically digitalized, eliminating transcription errors.
5. For free, a cheaper way of collecting data if sensors equipping automated vehicles are used for this endeavor.

This virtual transformation occurs in typical areas, including infrastructure design and building design and management (Ma & Liu, 2018). Disruptive high-tech scientific mechanisms like IoT, Big Data, AR, blockchain management, and AI are on the rise, strengthening the infrastructural system (Alaswad & Xiang, 2017). As a vital division of infrastructure frameworks, road maintenance and distress detection have motivated scientists in recent years. Several researchers inventively proposed procedures that may choose out road distress from images (Peng et al., 2010; Teizer, 2015). They demonstrated potential computerized methodologies of pavement distress detection techniques, which might moreover upgrade the manual assessment and boom administration effectiveness altogether. Another consideration scheme would be structure expansion based on methods to simultaneously lower costs and increase efficiency (Tizani & Mawdesley, 2011; El-Diraby & Osman, 2011; Koch et al., 2015;

Tedeschi & Benedetto, 2017). Existing research has confirmed the possibility of innovation that includes IoT and massive data on road maintenance.

In any case, within the component of IoT and digitalization in cities, road maintenance needs a more logical and step-by-step executive hierarchy that includes more data collection, assessment and analysis, information preparation, and decision-making assistance. Some of the recent studies took note of exceptionally exact issues (Chatterjee et al., 2018). Indeed, although their understanding can upgrade the effectiveness of road maintenance, they hardly address how to fix the entire road maintenance issue. The divergence stands between their analysis and operation in the actual world. The road administration framework encompasses diverse intentional modules. The implementations presently do not best depend upon a single module's plan. However, it depends upon coordination among interesting factors and modifications to the overall operation strategy and the environment. Existing studies show an absence of a unanimous attitude concerning road maintenance systems and thus do not conclude on the same types of hypotheses (Bilal et al., 2016). That is why this paper tries to fill this gap between the numerous studies that have been accomplished.

Using IoT and AI in a DT system, this paper aims to establish an intelligent administration system of urban road infrastructure and assist key stakeholders in overcoming existing obstacles in terms of urban infrastructure management. Concurrently, this paper will fill out the research gap considered as a lack of an integrated framework for intelligent monitoring of urban road infrastructure. In the system discussed in this paper, algorithms that enable smart infrastructure decision-making will be developed. SUIMS clarifies and briefs for the linked regulation division to improve by combining accessible processes with the traditional operation handle. Aside from that, the SUIMS is open to another connected computerized framework to accomplish collaborative improvement from the prospect of the intelligent city's capabilities.

The problem addressed is the lack of an intelligent management architecture for urban infrastructure in cities. Existing infrastructure management systems often suffer from inefficiencies, limited data utilization, and insufficient adaptability to the evolving needs of urban environments. This hinders the optimal operation, maintenance, and planning of critical infrastructure components such as transportation networks, energy systems, water supply, waste management, and public services.

The absence of an intelligent management architecture poses several challenges. Firstly, the lack of comprehensive data integration and analysis prevents holistic decision-making and hampers the ability to identify patterns, trends, and anomalies across different infrastructure sectors. This results in suboptimal resource allocation, reactive maintenance practices, and missed opportunities for cost savings and performance improvements.

Secondly, the traditional management approaches in urban infrastructure often lack the capability to leverage emerging technologies such as AI, ML, big data analytics, and IoT. These technologies have the potential to provide real-time monitoring, predictive maintenance, dynamic optimization, and automated decision-making, enabling more efficient and proactive management of urban infrastructure.

Furthermore, the existing infrastructure management systems may not adequately address the diverse needs of the urban population. They often overlook considerations of social equity, accessibility, and inclusivity, leading to disparities in access to infrastructure services and marginalization of certain communities.

Therefore, there is a pressing need to develop an intelligent management architecture for urban infrastructure that integrates data, advanced technologies, and inclusive principles. This architecture should enable comprehensive data collection, analysis, and visualization across different infrastructure sectors. It should also support real-time monitoring, predictive modeling, and proactive decision-making to optimize resource allocation, improve maintenance practices, and enhance the overall performance and resilience of urban infrastructure.

Additionally, the intelligent management architecture should prioritize inclusivity by considering the diverse needs of all individuals and communities. It should aim to eliminate barriers, promote equitable access to infrastructure services, and engage citizens in the decision-making processes to ensure their voices are heard and their requirements are met.

Addressing these challenges through the development and implementation of an intelligent management architecture for urban infrastructure will enable cities to enhance efficiency, sustainability, resilience, and livability, while fostering social inclusion and meeting the evolving needs of urban residents.

3.2 The proposed architecture

To develop an intelligent management architecture for urban infrastructure, the following method and framework can be proposed:

- Data integration and management
- Advanced analytics and decision-making
- Integration of emerging technologies
- Inclusive design and citizen engagement
- Scalability and interoperability
- Performance monitoring and continuous improvement

By following this method and framework, an intelligent management architecture for urban infrastructure can be developed and implemented, enabling cities to optimize the operation, maintenance, and planning of their infrastructure systems. It can lead to improved resource allocation, proactive maintenance practices, enhanced service delivery, and a more inclusive and resilient urban environment.

3.2.1 Fundamental useful modules

The concept of digitization involves the creation of a data-driven, computerized, and AI. To develop an efficient SUIMS, practical requirements need to be considered, with a key focus on incorporating "intelligence." This intelligence entails both internal coordination among sub-departments for planning purposes and external collaboration with other systems such as building CIM systems. The following are the essential components that contribute to the development of SUIMS, providing significant value.

3.2.2 Computerized data preparation

A complete and reliable appreciation of road conditions and an understanding the cause of deterioration are essential to selecting good road M&R strategies. Manual condition surveys are the standard way to examine street conditions (Capotosto, 2021). Therefore, applying this manual road condition evaluation results in poor resource allocation. To resolve this issue, a comprehensive understanding of road conditions is required. The workforce cannot bear such an overwhelming and robust workload despite this. The improvement of the IoT provides the opportunity to overcome this issue. Depending on different sensors, such as modern cameras, infrared cameras, and ground-penetrating radars, the IoT allows for component cooperation. These tools have delivered extensive assets with a reasonable budget (Bohn & Teizer, 2009). Street sensors are presently being used maturely. After being coordinated and equipped on the vehicle while driving, it can measure and exchange road characteristics (Capotosto, 2021; Tarabay, 2020).

By building up a comprehensive data collection and identifying the reason for deterioration based on the IoT, information on the current condition of the road is cost-effectively and reliably collected and transmitted for the advanced investigation to verify the reason for the deterioration that was suspected based on the observed distress.

3.2.3 Adequate information handling and examination

During the road condition detecting procedure, data grows at an exponential rate. Moreover, unprocessed data is unstructured and cannot be used to make decisions immediately. The data must be processed and examined to recover the information concealed in many disorganized data. The rapid advancement of tools has resulted in new perspectives and opportunities, and data analysis from several perspectives is critical when dealing with complex and diverse data. The practical methods of analysis are listed in Figure 3.2.

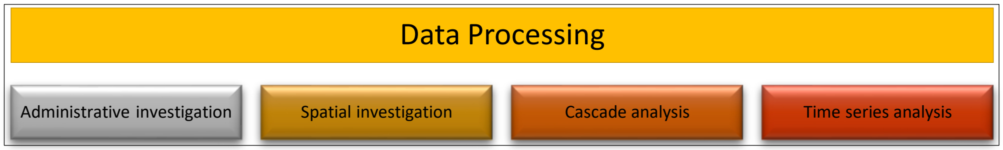

Figure 3.2 Process data from a unique perspective[1]

The administrative investigation makes a difference in analyzing suitable arrangements in specific circumstances, aiding directors in providing exact answers to diverse situations. The spatial examination is exceptionally valuable for analyzing location-based information and translating the spatial connections between various physical objects. Cascade investigation, still known as stream occasion investigation, makes a difference in analyzing numerous "progressive" databases. In other words, the real-time information stream will be analyzed to distinguish rare occasions.

To summarize, data analysis can assist supervisors in making decisions and taking appropriate actions. The development of advanced analytics strategies for large data is essential, and they assist stakeholders in gaining a broad picture of the situation and supporting their decisions. This preparation could be a valuable opportunity for the administrative organizations in a city.

3.2.4 Policymaking and information integration

The information must be considered to develop the appropriate choices after the information behind the data has been extracted from the information preparation and examination process. Information integration refers to the thorough use of a variety of data sources. Information integration aims to improve asset proficiency and efficient usage of different data categories.

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[1] Source: Almobaideen, W., Krayshan, R., Allan, M., & Saadeh, M. (2017). Internet of Things: Geographical Routing based on healthcare centers vicinity for mobile smart tourism destination. *Technological Forecasting and Social Change*, *123*, 342-350.

The ability to perform programmed classification, prioritization, and high-quality administration depend on information integration based on the PMS results.

Disintegration, cracking, distortion, surface treatment distresses, and skidding risks are frequent pavement distress types in a PMS. Traffic loading, environmental or climate impacts, drainage issues, materials quality concerns, construction deficiencies, and external contributors such as utility cuts are common causes of pavement deterioration. All need their tests to be distinguished and then treated accordingly. As shown in Table 3.2, the same work has been done in Châteauguay city, and a part of the required tests and intervention is displayed (L. Capotosto, 2021).

Table 3.2 Pavement deterioration types and required tests[1]

Name	Length (m)	Width (m)	Test characteristic	Intervention
Ch. Du Bord-de-l'Eau	366	5	Foundation (granular / water)	Pulvo-Stabilization
Bouchard street	39	6	Coated	Planning / Resurfacing

3.3 The approach of the designed performance-based management system

3.3.1 The detailed components of the framework

Engineers and academics across multiple industries are actively engaged in discussions and research related to IoT, big data, and other advanced technologies. Despite being in various stages of development, these innovations continue to progress. The integration of these advancements within a DT architecture has the potential to revolutionize traditional enterprises and significantly impact people's lives.

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[1] Source: Capotosto, L. (2021). *Développement d'une plateforme intégrée pour l'optimisation de la conception de la réhabilitation des chaussées* École de technologie supérieure]. Montreal.

By applying these modern advancements to street infrastructure, the efficiency of administration can be greatly enhanced, and valuable insights into administration preparedness can be coordinated. Analysts and engineers are exploring innovative approaches to improving road maintenance from diverse perspectives. If the systems of different organizations responsible for road maintenance within a city can be effectively integrated into a unified administrative framework, it will maximize efficiency and effectiveness in managing the road infrastructure.

The goal of upgrading the road maintenance architecture from a global perspective is to unify O&M systems, establish synchronized administration of all road maintenance stakeholders, and advance road maintenance systems. This DT framework must enhance street assessment management, support arrangements, mechanical equipment management, crisis management, and other capabilities. In addition, progress must be made in the logical assessment of street conditions and establishing a street condition monitoring component to fulfill needs and long-term patterns. There for both terms “Intelligence” and “Inclusive system” need to be deeply discussed.

Intelligence: in the context of a smart city management system, intelligence refers to the ability of the system to gather and analyze data from various sources, such as sensors, devices, and databases, to derive insights and make informed decisions. It involves using advanced technologies like AI, ML, and data analytics to process vast amounts of information and extract meaningful patterns, trends, and predictions. Intelligent systems can optimize resource allocation, enhance operational efficiency, and improve the overall functioning of a smart city.

Inclusive System: an inclusive system in the smart city management context emphasizes the goal of ensuring that the benefits and services provided by the smart city infrastructure and technologies are accessible and available to all citizens, regardless of their socio-economic status, physical abilities, or other demographic factors. It focuses on creating an environment where no one is left behind and everyone can participate and benefit from the smart city initiatives. An inclusive system aims to address the digital divide, promote social equity, and foster equal opportunities for all members of the community.

While intelligence in a smart city management system emphasizes the technological capabilities to process data and generate insights, an inclusive system highlights the importance of equity, accessibility, and inclusivity in the distribution of those benefits and services. Both aspects are crucial for the successful implementation and sustainable development of a smart city.

As a result, SUIMS is created to close any inconsistency and provide reliable decisions with the most efficient pre-arrangements. Theoretically, infrastructure maintenance is defined as detecting problems, researching them, and maintaining the normal state of their foundation. The SUIMS emphasizes the importance of utilizing all establishments and other resources more effectively and making acceptable choices based on the requirements of proper road maintenance regulations and directives and the reality of the existing situation. As a result, the SUIMS can be divided into three sections: identification and modeling infrastructures, a request for information, and assistance in policymaking. The interdependency between different components and the inclusive system is shown in Figure 3.3. This system is straightforwardly explained in section 3.4.

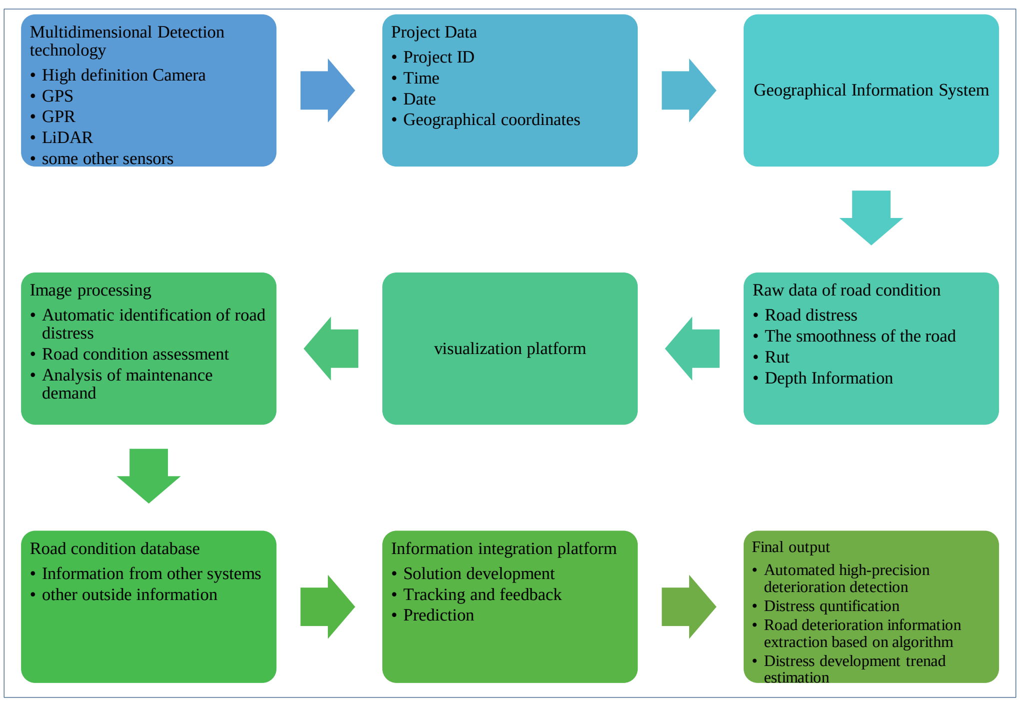

Figure 3.3 Structure of the performance-based designed system

3.3.2 Benefits of the performance-based system

The advantages can be expressed in four distinct categories. DT system planning is established on standard layouts. It is developed exceptionally into IoT, ML, and big data models that can be characterized as putting DTs on different scales like buildings (small scale), roads (moderate scale), and entire cities (large scale). Following are DT architecture specifics.

- Based on existing multi-tier planning, this planning is arranged in a five-layer pattern (As illustrated in Figure 3-1) for varied stratified zones from systems. Various infrastructures such as bridges, tunnels, buildings, and pavements are interconnected and operate across multiple coordinated and shared levels.
- By connecting different assets and data resources with analytical models, this planning permits the assimilation of three-dimensional spatial and georeferenced components with other databases.
- It is based on cloud computing and IoT architecture. It offers interoperability with a wide range of protocols and contexts and the strength to handle real-time sensors and distributed data in various patterns.
- Communication and transmission carriers with every user have been joined to link the inconsistency with human interactions and streets/cities.

3.4 Setting up a SUIMS

3.4.1 Roadway detection and modeling

The starting point of the entire system is road detection. Existing innovation can assist city managers in dealing with underperformance in their workforce. Different sensors, such as a 3D road surface data-collection device, a high-definition camera, and other critical facilities, such as LiDAR, encoders, and GPS, are required to meet the information collection needs. The use of detection tools will replace manual assessment. Multidimensional information is acquired in a powerful and timely manner through ordinary timepieces.

The data gathered includes unprocessed data on roadway conditions, GPS data, and other specification information. This data can be reflected using visualization software. The 3D laser point cloud technique will represent road conditions, which have been used in development design for a long time (Ma & Liu, 2018). The proposed prototype can assist in real-time screening and visualization of road conditions.

A visualization stage is developed by applying AR innovation by coordinating visual data from all streets. The data gathered will be organized and incorporated into the platform. It is beneficial for decision-makers to access comprehensive street data such as distress locations, test records, and other analytical criteria.

3.4.2 Data Investigation

3.4.2.1 Automatic coordination of road distress

Following the road distress data extraction from the layout, it is processed using the image detection innovation. Traffic events will be accordingly categorized, aiding in the enhancement of the subsequent preparation. Distresses are grouped into many categories, such as broken potholes and thermal and longitudinal cracks, and classification criteria might be balanced to meet administrative needs.

3.4.2.2 Road condition assessment

Making decisions is also made easier by evaluating road conditions. There are various principles for assessing the road's condition. The MQI (Maintenance Quality Index) evaluates the serviceability of infrastructures, pavements, overpasses, tunnels, and roadside amenities. The Pavement Quality Index (PQI) is a pavement evaluation index that counts as the most critical component. These two indices are both important indicators for assessing road conditions. Figure 3.4 depicts the elements of the two indices.

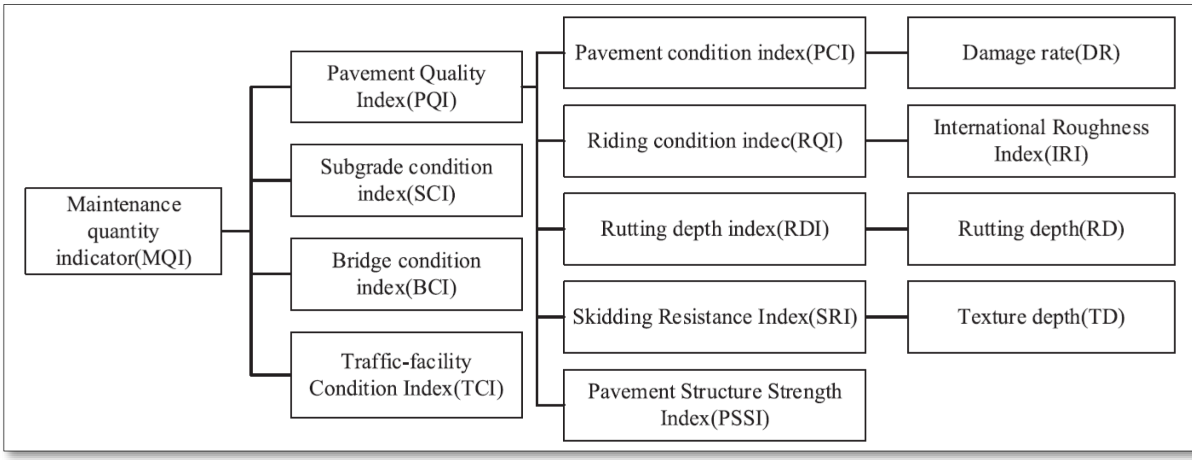

Figure 3.4 The peripheral indices[1]

3.4.2.3 Examination of support request

The city's massive road network has various distinct and sophisticated support demands. As a result, it is critical to prioritize them in terms of importance. Decision-makers can determine which of hundreds of street maintenance requests are the most urgent according to their assessment standard based on the conditions of various streets and the specific problems. Consequently, the restoration of severely damaged streets to their previous state of maintenance significance will be prioritized. This approach has the potential to reduce the drawbacks experienced by both motorists and pedestrians.

[1] Source: Almobaideen, W., Krayshan, R., Allan, M., & Saadeh, M. (2017). Internet of Things: Geographical Routing based on healthcare centers vicinity for mobile smart tourism destination. *Technological Forecasting and Social Change*, *123*, 342-350.

3.4.3 Road status database

Over time, the amount of data collected on the complex road network grows, and further investigation requires the data acquired. For example, it is crucial to investigate the timelines of road maintenance requests for reacting to and improving the road structure framework. Creating a road condition database to coordinate this vital information is critical. After the status of a specific street has been determined through data collection and investigation, policymakers can make decisions based on a condition-based maintenance agenda that underlines the use of sensor-based accuracy models and data aggregated from observed working frameworks to create procedures for checking and maintaining framework stability (Alaswad & Xiang, 2017). By collecting information and assessing conditions, condition-based maintenance makes a difference in decision-making (Teizer, 2015). Road observation information will be utilized to confirm the requirement for a distinct repair action and plan numerous maintenance activities (Jardine et al., 2006; Peng et al., 2010).

3.4.4 Policymaking

3.4.4.1 Synergetic system

Although different urban practical frameworks such as transportation, communication, industry, and energy have demonstrated a strong improvement tendency over the previous decades of the urban infrastructure, it is still not optimal enough. The lap over of these frameworks has resulted in a wide range of urban management concerns, including repeated financing. Enterprises' inefficiency between urban frameworks eventually inhibits a city's "smartness." Furthermore, the involvement of various administrative organizations could be an inclusive situation. One instance is data allocation, in which all offices would be advantageous having access to a broader range of data. Vigorous control of local personnel quantity and traffic flow data will help the road infrastructure department make scientific decisions.

During the decision-making process, supervisors will evaluate data from various relevant frameworks. As a result, information from multiple frameworks is integrated with data from a street condition database in SUIMS, which influences the data integration stage. Other external data may be required in the future, leaving the data integration stage open to potentially valuable data.

3.4.4.2 Assessment and prediction

The information synthesis step provides key facts to decision-makers that can be consistently included. Supervisors use this information to establish road maintenance plans. Following decision-making, observation and criticism will aid in revealing framework flaws and continuously progressing future framework design.

Furthermore, city managers can obtain the progressing patterns of road troubles by utilizing rich data and selecting appropriate data-driven strategies to help with future decision-making.

3.5 Conclusion

With a focus on DT implementations and the need to incorporate all the benefits of DTs into current routine life, this paper first presented a complete examination of DT definitions and implementations in the intelligent urban infrastructure management system. An in-depth investigation was carried out to focus on the limitations of establishing DTs from a data processing standpoint (interoperability, data source variability, data interconnection, and data integrity). The integration of big data applications empowered by IoT and AR has become increasingly crucial for smart and sustainable cities. These applications play a significant role in enhancing the operational efficiency and planning capabilities of cities, further advancing their commitment to intelligent development. Therefore, designing SUIMS that incorporate these technologies to move forward an intelligent city seems crucial. This study used three subsections to form the SUIMS: data preparation, information extraction, and policymaking based on information integration. The SUIMS has the following advantages over the traditional administrative framework:

- High-precision automatic detection of road disintegration,
- 3D distress analysis,
- Using an algorithm, extracting data about road degradation,
- Collaboration with other city systems,
- Predicting problematic improvement tendencies.

CHAPTER 4

DESIGNING AND BUILDING AN INTELLIGENT PAVEMENT MANAGEMENT SYSTEM FOR URBAN ROAD NETWORKS

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This chapter presents the paper published in the Sustainability journal. This paper addresses the second research question and develops an urban PMS emphasizing all different modules of the urban infrastructure network in data and analysis. This paper has materialized the research's second objective for designing and building an intelligent urban infrastructure management system for urban pavements to monitor and manage the instrumentation of the planned structure using smart sensors. It provides an overview of the system components and their interactions in the form of an integrated framework which starts with getting appropriate data from reliable sensors, which are LiDAR and RGB images, then making all the analysis in a GIS and Mechanistic-Empirical Pavement Design Guide (MEPDG) platform, and finally providing a 3D model of the study area. The concerns and opinions of city officials are also considered in the final output of the designed CityEngine model. The most important contribution of this paper is to present the input and output flow of the pavement management mechanism designed in this thesis to make it ready for a 3D urban management model.

Abstract

In terms of urban public expenditures, pavement maintenance plays a significant role. The road network is to be upgraded and preserved at the least cost and with minor disturbance to the public. Public complaints and scheduled road reviews are the two primary sources of road maintenance under the smart PMS plan. In contrast, if the damages are not treated immediately, they will worsen and increase by the time they are treated. By leveraging accurate data from sensors, infrastructure, and networked devices, cities that use smart infrastructure will improve capabilities, support sustainability, and drive economic growth in their road network. This research elaborates on all the different modules of an intelligent urban infrastructure management system emphasizing the city pavement network. In the first step, the 3D mobile LiDAR sensor is applied as the data collection tool, accompanied by an RGB camera installed on top of a car. Although 3D mobile LiDAR data has gained popularity, their vast capabilities in autonomous vehicles lack precise detection of pavement distresses, including cracks. As a result, utilizing the RGB images may help extract distresses properly. Two approaches are developed to conduct the data analysis in this paper: (1) ArcGIS pro, developed by Esri Inc., which includes noise removal, Digital Elevation Model (DEM) generation, and pavement and building footprint extraction; (2) To design the most appropriate pavement for each road section, Pavement Mechanistic-Empirical Design Guide (AASHTOWare PMED) is used to assess site specifications like traffic, weather, subbase, and current pavement statuses. For the 3D visualization module, CityEngine is used to provide the 3D city model and help visualize the impact of every distress on the policy-making procedure.

Keywords: Urban Infrastructure, GIS, Pavement, 3D visualization

4.1 Introduction

Roads are critical to the economic growth and development of a city. Providing access to employment, social, health, and educational services is another vital road network function in reducing poverty. As a result, researchers and city officials have been interested in studying road maintenance as a significant aspect of urban infrastructure that includes a network of pavements in all surrounding cities. In general, and in all weather conditions, pavements offer safe and comfortable rides for all cars at average speeds. The life cycle of a road can be measured by the number of years it has been used for its intended purpose. Due to the significant importance of road network health and its maintenance in citizens' daily life, this topic should be appropriately addressed in academic plans.

The condition of a city's road infrastructure directly impacts people's quality of life (Hanák et al., 2014), including safety, residents' health, work, economic opportunities, and leisure activities (Hanák et al., 2014; Ivan Marović, 2013). As a result, because every action is complicated and socially sensitive, it requires extensive consideration. To cope with such issues, municipalities frequently face significant challenges concerning planning development, for example, when they need to find a solution that fits the expectations of all stakeholders, which is critical while having to be consistent with the planned development concept at the same time. Public decision-making processes are constrained by specified budgeting for construction, maintenance, and remediation work on road infrastructure. Prioritizing projects is a crucial and challenging issue that must be resolved to effectively develop and implement a road infrastructure plan (Jajac et al., 2015). Therefore, pavement evaluation regularly is essential to each municipality's agenda.

Considering either municipal or technical aspects of the urban pavement maintenance procedure, it is essential to determine each road section's condition and rate of pavement deterioration to plan for the financial costs of a maintenance strategy in a municipal budgeting program. A technical evaluation of the road network quality based on a PMS is required to meet the optimal structural rehabilitation design and future budget needs. It has various tools and methods which help decision-makers determine the most appropriate strategy for maintaining, evaluating, and providing pavements over a while (AASHTO, 2012).

In the last decades, there have been some attempts to run the most efficient knowledge-based PMS all around the world, they were successful, but some inaccurate results remain. With the advent of innovative technologies like the IoT, ML, and AI, the idea of applying intelligent urban infrastructure to overcome the defects of traditional systems is growing exponentially.

Smart urban infrastructures are founded on four principles: data, analytics, feedback, and flexibility in an urban environment. In addition to their physical structure (cables, sensors, etc.), a city's smart infrastructure can be characterized as a cyber-physical system that integrates all its aspects using various technology tools. These tools help acquire and analyze data to achieve efficiency, sustainability, productivity, and safety goals. In a city, smart infrastructure refers to an intelligent system that leverages a data feedback loop to improve decision-making. Sensor data can measure, analyze, monitor, communicate, and act on such an intelligent system (Smart infrastructures: essential for smart cities). The following list describes the features that compose an intelligent urban infrastructures system:

- *Data*: It is an essential element that an intelligent system needs to perform and the raw material that an intelligent infrastructure needs to work correctly.
- *Analytics*: Information analysis is essential to obtain reliable data for decision-making.
- *Feedback*: Any intelligent system must have a data feedback loop. This feedback is visible when data is collected, utilized, and used to improve the system's functionality.
- *Adaptability*: Smart systems can adjust to current demands and accommodate future needs.

Considering the intelligent urban infrastructures as a spatial phenomenon in nature and the capacities of GIS in the field of working with spatial data, the integration of GIS and PMS will move forward to resolve the taxpayers' concerns in a city. GIS is the best tool for improving pavement management since it can evaluate geographical data, especially with features like a graphical depiction of pavement conditions. Government agencies are gradually integrating PMS data into GIS as GIS is used more frequently and becomes more valuable due to technological advancements in computer hardware and software. Flexible database editing and the ability to view statistics, charts, and the results of database queries are all advantages of this integration. Additional advantages include pavement management analysis on a road system map, dynamic highway section color coding, and access to sectional data through graphical 3D GIS models.

Reconstruction of 3D GIS models, high-definition mapping, and new applications for cities require accurate and efficient data collection and scene perception of urban environments (Campbell et al., 2010). Over the previous decade, many urban modeling studies have relied chiefly on aerial and 2D satellite data (Crommelinck et al., 2016; Ma et al., 2017). Additionally, self-driving car research has relied extensively on 2D photos acquired by digital cameras (Ros et al., 2015). Therefore, the need for an interrelated system of both 3D GIS and PMS is urgently being sensed among researchers.

Providing pavement design methods in a 3D GIS model with different applications being utilized to optimize the serviceability of each road section is highly demanded. Based on this paper's state of the art, no study has covered this issue until now. Both design and implementation of a SUIMS, which is developed here, could clarify and brief the linked regulation to improve dealing with massive datasets in PMS by combining accessible processes and overcoming the traditional operation difficulties simultaneously. Additionally, the SUIMS will take advantage of a connected computerized framework integrating the city's public capabilities to accomplish collaborative improvement, which has rarely been discussed earlier.

A city pavement network management system emphasizing the different components of an intelligent urban infrastructure management system is elaborated on in this paper. First, a mobile LiDAR sensor accompanied by a camera mounted on top of a car is used to collect data. Even though 3D mobile LiDAR data has become increasingly popular, they cannot accurately detect pavement distress, such as cracks. By using RGB images, it may be possible to extract distresses correctly. Like every other urban management system, for the designed structure, it is necessary to make the analysis and provide the results in an appropriate visualized form in the ultimate step. Therefore, the most significant contributions of this paper are:

1. Build an urban outdoor point cloud dataset pointwise labeled at a large scale for SUIMS in terms of pavements.
2. Investigate an integrated road network consisting of their position (via 3D LiDAR point cloud) besides their attribute information and the detected distress through RGB images.
3. Produce a detailed 3D intelligent PMS based on city officers' decision-making preferences.

4.2 Literature review

Algorithms that enable intelligent infrastructure decision-making, including PMS, are needed to measure, monitor, analyze, and integrate decisions in urban road networks. Therefore, to move forward to SUIMS, having access to the most beneficial pavement design in a PMS is vital. A glance at the different tools and their interrelationship in a city, including such SUIMS, is shown in Figure 4.1.

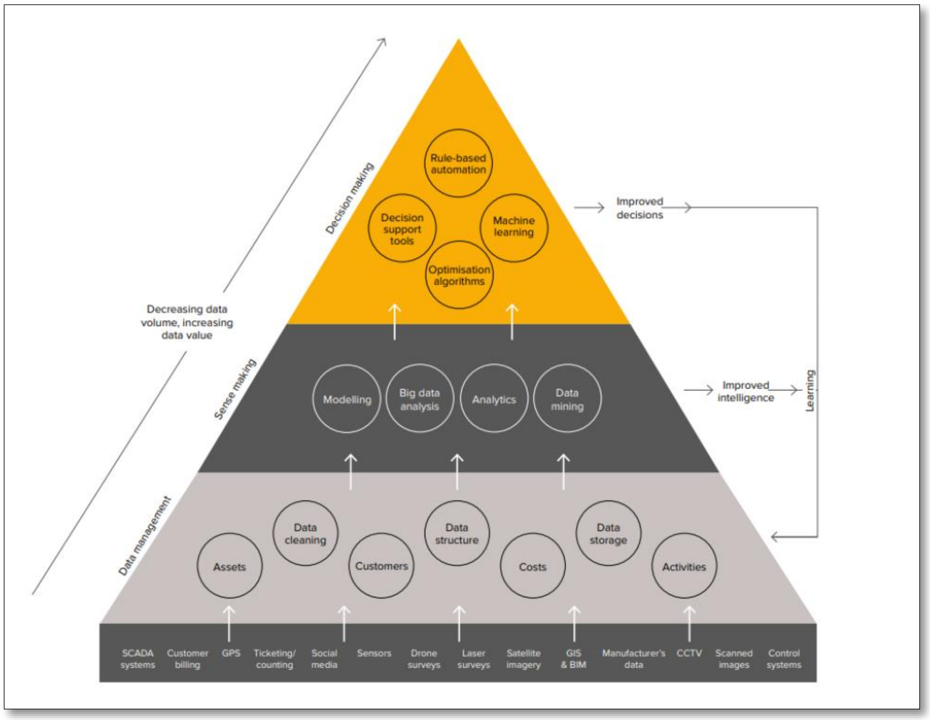

Figure 4.1 Different components and tools of a SUIMS

A key component of establishing the PMS in a city is monitoring the status of road structures to ensure that the pavement is in ideal condition (Mubaraki, 2014). It costs millions of dollars every year for each city. Various management information systems were established to deal with such complexity. Typically, one of two ways is used: (1) Using specially equipped vehicles manually or (2) automatically conducting distress surveys. However, because these investigation methods only record the distresses that has already occurred, they are reactive rather than proactive in identifying deterioration.

Two significant variables are considered when assessing the pavement quality: (1) the existing road quality and (2) the quantity, along with the intensity of distress signals. The category of distress and how often and how severe it occurs are all critical indicators of structural appropriateness, material scarcity, and the risk of additional degradation (Chong, 1982). Surface distress, including potholes or cracking on thicker pavements, may not be symptomatic of structural degradation. Surface depressions cannot be relied upon to signal structural conditions when pavement preservation efforts intervene early to maintain and prolong pavement life (Lajnef et al., 2013).

As a result, the required data to do the investigation over the urban pavements and build the GIS-based smart PMS would be as the two following categories:

- Geometrical data of the pavements is captured by applying 3D mobile LiDAR and RGB photos with a vehicle outfitted with the necessary equipment for the distress detection phase.
- Attribute data of each road section consisting of general project information, design criteria, traffic data (vehicle/day), climate data, structure, and layering data, including material properties for the pavement design phase.

4.2.1 Data

4.2.1.1 Geometrical data

3D point clouds created by LiDAR equipment are beneficial for spatial analysis of 2D pictures that lack georeferenced 3D data (Ma et al., 2019; Remondino, 2011). Moreover, point clouds are unorganized, oriented irregularly, and frequently have a large volume. Due to the complexity of data collection, portable devices that connect with Mobile Laser Scanning (MLS) sensors, location devices (e.g., GNSS), and two-dimensional cameras are turning out to be amazingly well known in looking over self-driving vehicles and metropolitan regions (Levinson et al., 2011; Yang et al., 2018).

Producing high-quality handwritten labels from LiDAR and RGB-D sensor datasets is complex and computationally expensive since they often contain much data and noise.

According to some recent research, the following are part of public outdoor point cloud datasets that are freely available.

- MLS and SICK sensors (Abbreviation for an object between sensor and background (SICK)) were used to create Oakland 3D, in the first instance of its kind, as an outdoor point cloud (Munoz et al., 2009). The LiDAR device used here is mono fiber with a low point density mono fiber. This dataset has around 1.6 million points, sorted into 44 classes. However, only five classifications were examined in the literature: vegetation, wire, pole, ground, and facade. Because this dataset is small, lightweight networks can be constructed and tested.
- The data file of iQmulus (Brédif et al.) was obtained using Stereopolis II (Paparoditis et al., 2012) in Paris from the IQmulus & TerraMobilita Contest. A monofiber LiDAR called "Riegl LMS-Q120i" was applied to capture the spatial information data. There are around 300 million points within the entire dataset divided into 22 classes. Consequently, for the contest dataset, just one sample was shared with the public: 12 million observations in a 200-meter domain with eight accurate classifications. The classification quality in this dataset is low due to the obstructive sensing device, which is monofiber, and the labeling process used; the image appears distorted.
- Semantic 3D (Hackel et al., 2017) uses terrestrial laser scanners to collect data, and it has a far better point density and precision than the other datasets. This dataset contained eight class labels. However, static laser scanners can only capture a limited number of perspectives, and equivalent datasets are difficult to achieve in practice.
- In recent years, the Paris-Lille-3D collection has been widely used as a point cloud dataset for outdoor applications that has grown in popularity due to its advantages (Roynard et al., 2018). Data was collected using an operational support system and a Velodyne HDL32E LiDAR, with just a point frequency and analysis precision comparable to that of self-driving automobile point clouds. Over 140 million points and specific labeling for 50 different points are included in the collection, which spans about 2 kilometers. The dataset uses nine classes for semantic segmentation in the benchmarks.

- SemanticKITTI is one of the most novel and comprehensive semantic segmentation datasets publicly available (Behley et al., 2019). The KITTI dataset was utilized to annotate the dataset better (Geiger et al., 2012). This dataset incorporates more than 4.5 billion points encompassing 40 kilometers, and each consecutive scan is tagged with 25 classifications for semantic segmentation assessment. The indicated dataset focuses on algorithms for self-driving vehicles.
- Toronto-3D (Tan et al., 2020): A Teledyne Optech Maverick car-mounted MLS device was used to capture actual point clouds for all this dataset. A 32-line LiDAR scanner, a GNSS, a Ladybug-5 360-degree camera, and a Synchronous Localization and Mapping (SLAM) structure are all part of the system. With an accuracy of more than 3 cm and a field of vision angle of -10 to +30 degrees in the vertical direction, LiDAR technology can capture point clouds at a rate of up to 700,000 per second. LMS Pro software was used to process the gathered point clouds further. Each point was assigned a natural color (RGB) regarding the imaging camera. Following that, points on the upper level of the pavement will be broken into frames, each of which will cover a road segment. The camera will produce two-dimensional footage that has been preprocessed to retrieve frames. Each frame will be classified as either having pavement distress or not having pavement distress.

4.2.1.2 Attribute data

For pavement design, three fundamental parameters must be considered: the characteristics of the subgrade on which the pavement is placed, the applied loads, and the environment (Local calibration of the mechanistic empirical design software for Wisconsin 2012). To begin with, the subgrade's depth will affect the pavement's design. Pavement layer thickness, the number of layers, load restrictions during the seasonal change, and any improvements to the subgrade's stiffness and drainage are determined by the stiffness and drainage of the sub-base.

As a secondary input (both in a mixed design and structural design), the anticipated traffic load is also a primary concern. In addition to pavement composition, layer type, and thickness, traffic loads must also be considered to determine pavement life. Environmental factors can also have an impact on pavement performance. Various environmental factors, including temperature, moisture, and ice formation, can influence pavement durability, binder rheology, structural support, as well as the longevity and failure of the pavement.

4.2.2 Analysis tool

Access to the most efficient PMS scheme needs introducing and comparing the well-known systems of mechanical pavement designs. The AASHTO 1993 design technique is widely employed in the mechanical design of flexible roads (AASHTO, 2012). The pavement design procedure for road sections with different temperatures and varied subgrade circumstances has limitations compared to the AASHTO 1993 Guide for Design of Pavement Structures (Bayomy, 2010; Elfino et al., 2010). The calculated drainage layer coefficients are one of the method's significant flaws. Together with the seasonal shift in the robust subbase modulus, these coefficients are the only environmental factors in the AASHTO 1993 design technique.

Additionally, environmental conditions have a severe effect on pavements. As a result, there is a focus on employing a cost-effective pavement model that results in detailed designs and, as a result, superior pavement function over time. Closed-form structures are applied in the MEPDG (Gusto, 2016) to evaluate city interactions, weather conditions, base developments, and laboratory surveys of all different element properties to anticipate the actions of the several pavements plans if they are in service (Elfino et al., 2010). MEPDG is projected to deliver more dependable pavement designs than the AASHTO 1993 when adjusted to local conditions. In contrast to AASHTO 1993, MEPDG examines the effects of temperature and relative humidity on layers of pavement and their mechanical properties.

According to a correlation study of the MEPDG and AASHTO 1993 design guide (El-shaib et al., 2017), even though all pavement sections were calculated using the AASHTO 1993 technique for the equal service failure, they behaved differently as forecasted by MEPDG. The MEPDG anticipated act of the AASHTO 1993 planned pavement structures changed significantly as traffic levels increased and subgrade strength decreased. This difference is significant for various meteorological circumstances, which have an exponential effect on the quality of road infrastructure. Access to the PMED report of a single road section requires sufficient and accurate data to be used as input for the PMED step. Therefore, before every action, the municipalities need access to these data. Furthermore, they must integrate the MEPDG design method with the 3D GIS models to get the most efficient urban infrastructure management strategy.

Soil Water Characteristics Curve (SWCC) characteristics and other soil conditions needed by the Enhanced Integrated Climatic Module (EICM) within the MEPDG are the focus of a decisive study on the extensive national soil database (Kim, 2011). It offers a GIS-based technique for precisely superimposing any road section on soil maps. Additionally, there is ongoing research to monitor sites and collect data for the MEPDG prediction models' calibration, as well as to evaluate the impact of various materials and construction techniques on pavement performance (Tsai & Wu, 2019). To visualize the sites, a GIS project and add-in tools were created. Additionally, the MEPDG's projected distresses on interstate areas were confirmed, and the contrasts between the MEPDG's designs and those of the AASHTO 1972 Interim Design Guide were reviewed to offer recommendations on how to apply the MEPDG.

4.2.3 Visualization

Aside from the data and analysis required for the SUIMS, visualization tools are also needed to represent the productivity of the proposed architecture. As a result, GIS has recently gained widespread popularity among urban researchers due to its potential and ability to "generate support systems, decision-making architectures integrating a combination of AI and ML, urban expansion models, and software visualization techniques to help community-based strategies" (Brail & Klosterman, 2001).

The development of visualization products like CityEngine for designing, storing, and interchange 3D city and scene layouts led to recent advances in 3DGIS and urban data modeling. GIS is no longer 2D but also 3D. The ability to create 3D city models in a GIS context will enable a variety of tasks, such as cadaster, public safety, urban infrastructure management, and traffic control, to take on new dimensions. CityEngine defines a rule-based schema for the most compatible topographic features in metropolitan and local models that incorporate topological and semantic characteristics. It also includes adding detectable features to the data while maintaining semantic compatibility.

4.3 Methodology

In recent years, the advancements in ICTs have posed a significant challenge to the previously predictable nature of urban infrastructure services. One notable innovation in this regard is smart pavement, which brings numerous advantages to both road users and the agencies involved in the construction and maintenance of roads. A method exhibiting the SUIMS intended for this paper's purpose is elaborated in Figure 4.2 to fulfill this objective.

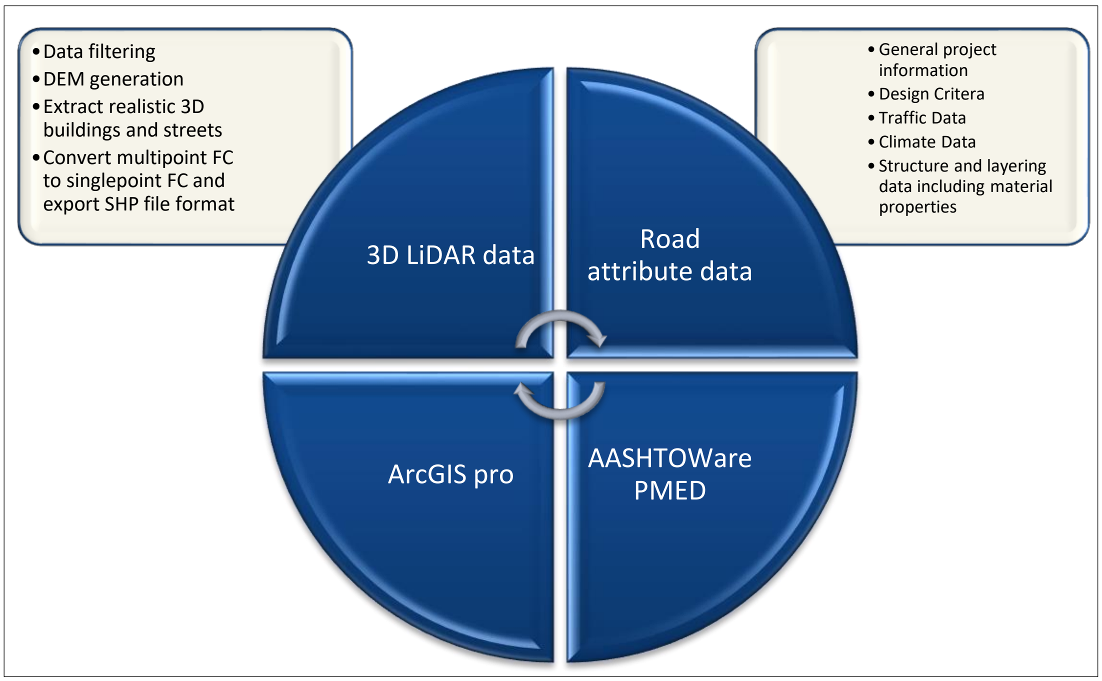

Figure 4.2 Workflow of the methodology

4.3.1 Data

4.3.1.1 Data acquisition vehicle

A sensor mounted on a vehicle is required to collect road data. The device includes a LiDAR and a camera fixed together in a solid frame. This research used the data collected recently (Tarabay, 2020). The LiDAR installed for data collecting is the Ouster os-16 channel (The specification of this LiDAR sensor is provided in Table 4.1). It is based on the concept of time of flight. Four separate signals are acquired with this LiDAR ("Hardware User Guide," 2019): the first one is "range," which calculates the length between the sensor and the object. The next is "reflectivity," which yields scaled readings depending on the sensor sensitivities within that range and device sensation within that spectrum. The third category is "signal," which determines how strong returned signals are. The last is "ambient," which also produces the backlight measurement's strength.

Table 4.1 Ouster OS-1 specifications[19]

Specifications	3D LiDAR (Ouster OS-116ch)
3D points/ profile	200 to 400 (4 m Field of View (FoV))
Car’s velocity	70 - 100 km/h
Distance between profiles	7 - 15 cm
X-axis resolution	1.1 to 2.4 cm
Lateral FoV	Up to 100 m
Precision on the Z-axis	3 cm
Frequency of sampling	160 - 320 profiles/s

[19] Source: Hardware User Guide. (2019). In *OS1-16/64 High Resolution Imaging Lidar*.

The hardware is positioned two meters above the ground on the top of a car. The configuration setup on top of the car is shown in Figure 4.3. The LiDAR and camera are angled at a 50-degree angle toward the ground. Both sensors cover an area of two*four (square meters). At 10Hz and 20 Hz, 512 x 16 and 256 x 16 pixels are the resolutions of LiDAR scanning. At 120 frames per second, the camera resolution is 1920 x 1080 pixels. The car can reach speeds of up to 40 kilometers per hour.

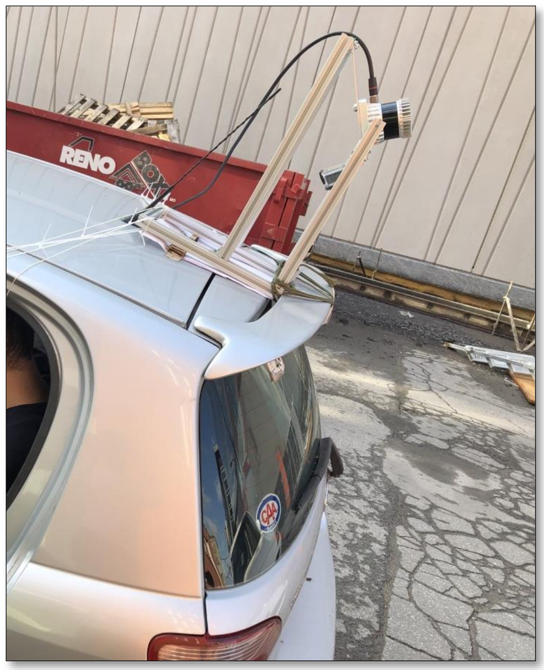

Figure 4.3 The data collection sensor[20]

4.3.1.2 3D mobile LiDAR data and RGB camera

The 3D LiDAR sensor will produce three-dimensional point clouds in the study area. By minimizing the LiDAR field of view, the road surface can be obtained by removing data that

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[20] Source: Tarabay, N. (2020). *Pavement Distress Detection with Conventional Self-Driving* ÉCOLE DE TECHNOLOGIE SUPÉRIEURE].

is not relevant to the road surface. Since the LiDAR data is not an excellent choice for distress detection goals, the RGB cameras are being used simultaneously for video recording. Therefore, the areas will be divided into video frames on the road surface, each covering a section of the road. The result of the camera is a two-dimensional video that has been obtained to extract frames. Each frame is assigned to one of two categories using the Convolutional Neural Network (CNN): (1) pavement distress or (2) no pavement distress (Tarabay, 2020).

A CNN is an ML model designed to learn spatial hierarchies of information automatically and adaptively, from low-level to high-level patterns, while processing data with a grid pattern, such as pictures. Object detection is one of CNN's most effective uses. This study employs the convolutional layer, composed of several kernels, to extract distress features from CNN. The number and size of kernels in a convolutional layer, which should be suitable for object recognition, is a crucial parameter. Another intriguing study found that it is possible to successfully recognize distress (Tong et al., 2017). The pooling layer is utilized by either max pooling or mean pooling to lessen the complexity of imported data to decrease the danger of overfitting (Li et al., 2021).

To identify and localize distresses, feature maps created by convolutional layers and pooling layers are imported into SoftMax layers and regression layers. Here, cracking is the only type of pavement strain that is considered. The results of a regression layer are the location of distresses, whereas the results of a SoftMax layer classify the image frames used in this paper as cracked or non-cracked ones.

4.3.1.3 Road attribute data

As stated in the preceding sections, the design and implementation of SUIMS focusing on a PMS must meet specific criteria. To reach these goals, a pavement design system should be developed. The primary purpose of pavement design is to construct a low-cost road surface that fulfills site-specific efficiency, service life, and regulatory standards. Pavement design is not a straightforward process, and numerous factors affect pavement performance, making analysis challenging (Tarabay, 2020). It necessitates a thorough knowledge of soils and construction materials and their behavior under varying traffic loads and weather conditions (Kazmierowski, 2013).

One of the essential pavement design aspects is traffic loading, which includes road congestion, load factors and distribution (trucks, cars, etc.), tire pressures, and suspension system characteristics. Rainfall, humidity in the pavement layers, temperature variations, and defrost periods are all environmental concerns. The subgrade soil, moisture content, and other physical factors impact pavement design (Kazmierowski, 2013). This study benefited from the data produced in a recent survey (Luigi Capotosto, 2021). The available data are as follows:

- Name, start and endpoint, length, width, and functional class of the roads.
- Traffic data (vehicle/day).
- Comfort index and estimated international roughness index (IRI).
- Primary diagnosis of causes of deterioration.
- Tests and actions made by the public work department and cost of work.
- Cost to users (annual cost).

4.3.2 Analysis tools

4.3.2.1 Spatial analysis with ArcGIS pro

Roads and buildings are two LiDAR points divided into several groups and categories. A classification can be applied to each LiDAR point to identify the type of object that reflected the laser pulse. The different classes are defined in the .las file using numeric integer codes, as seen in Figure 4.4.

Figure 4.4 Different integer codes in a .las file

The next spatial analysis step after getting road surfaces and buildings from the las dataset would be as follows:

- Data filtering to remove all noises.
- Digital Elevation Model (DEM) production.
- Realistic building and street pavement generation.
- Multipoint feature conversion into a mono-point feature class.
- Export the single point feature class as .shp files.

Thus, the outputs are a polyline shapefile with the road surface and a polygon shapefile with the building footprints in two different shapefile layers for importing into the final visualization and decision-making step. It should be marked that the extraction of building footprints in this study is just for visualization purposes in the 3D city model. There is no analysis of the building's footprints later.

4.3.2.2 Pavement design analysis with AASHTOWare PMED

A notable change in the MEPDG is how pavement design is analyzed. The conventional method involves considering various inputs and determining the design requirements for the pavement structure. Mechanics-empirical pavement design relies on a trial-and-error model of pavement structure design and information from traffic and climate. Inputs like load and environmental factors can be modeled by MEPDG software to calculate how the trial design responds to their effects. Upon doing so, an estimate can be made as to how much damage will be sustained over time to the pavement due to deterioration in ride quality and the distressing of the pavement.

4.3.3 Decision-making and visualization

An urban environment and its development are often reflected in the use of GIS. GIS is adapted to deal with spatial and visualization challenges connected with multi-scale geographical data from a technical standpoint in an urban environment. The potential of a GIS to create added information by combining incompatible datasets with a suitable geographical referencing system is exclusive (Goodchild et al., 1993). Therefore, in this paper, since the integrated GIS data and MEPDG results require a platform for displaying the research results, CityEngine is applied.

Based on these capabilities, in this step of the methodology, which is the final stage, first, the result of data analysis based on the combination of the previous two stages (spatial analysis and PMED) will enter the CityEngine and then based on the priorities of the city officers and macro-management policies that will be the criterion in each executive project, the appropriate rules will be applied. Then, for the visualization goal, a three-dimensional model will be prepared.

The geometry type of street axes is a line. The attribute table of streets consists of street names, lane type, speed limit, the existence of sidewalks, the presence of cracks, traffic data (vehicle/day), comfort index and estimated IRI, and primary diagnosis of causes of deterioration for each road section, tests and actions made by the public work department and cost of work, the cost to users (annual cost), and internal performance (rate of return). The geometry building footprint data is a polygon. The attribute table of building footprints consists of the building type, the height of buildings, and the number of floors.

4.4 Implementation and expected results

4.4.1 Study area

A small to medium-sized city in the Canadian province of Québec, Châteauguay has a road network that spans approximately 500 kilometers and a replacement value of $1 billion. It is seeing rapid residential and industrial growth. Due to an outdated network, increased traffic, and numerous roads, pavement degradation occurs more quickly than anticipated. The issue, like that of other Canadian municipalities, is that the yearly budget is inadequate to sustain these constantly deteriorating roads to an acceptable level. As a result, a significant backlog of M&R work must either be completed immediately or delayed at a higher cost. The streets of this study area are extracted from (Tarabay, 2020) as the data of this paper. The building of the study area is presented to provide a better 3D city model and show a more realistic result. The two analysis and visualization sections were conducted accordingly, and the results presented an urban environment, and its development is often reflected in the use of GIS.

4.4.2 Data establishment

As mentioned in section 4.3.1.2, the data in LiDAR is unstructured and unordered. Consequently, it cannot be used for the next steps unless preprocessed. Blunders are common in LiDAR data, and they can be created by photon scattering in a returned laser pulse, which causes noise. As a result, once the point cloud data has been converted to a LAS dataset using Cloud compare software, the dataset must be imported into ArcGIS Pro for additional data preparation, including noise removal and then acquiring the geometrical pavement shapes. In this implementation stage, access to the condition of the roads is available. However, the database still suffers from a lack of classified data in terms of cracks as the essential pavement distress.

A low-cost action camera is used in addition to the LiDAR sensor on top of a car to acquire pavement data. At a maximum speed of 40 km/h, footage on arterial roads is recorded. Action cameras are famous for capturing action footage from the shooter's perspective because they are small and simple to set up. The camera is angled at a 40-degree angle toward the pavement. This design can collect a 4*2 square meters road section as a sample unit of pixels, meaning 1 pixel covers around 1 mm. The output is then entered into a CNN designed to identify and classify the frames. Based on (Tarabay, 2020), using RGB-camera image frames as an input to the CNN is recommended to get the most accurate classified data. This CNN in this paper focuses on identifying the cracks as the pavement distresses. After applying the CNN, there are two categories of frames: (1) including cracks and (2) without cracks.

Numerous methods have been devised to locate and classify pavement cracks. The standard area convolution neural network pipeline consists of three phases: (1) area suggestions, (2) object detection, and (3) classifying. The technique has been improved further so that instead of providing a boundary, the object's boundaries are additionally recognized (He et al., 2017). It has been broken down into three primary stages to realize the multiple stages of detection and segmentation (Tarabay, 2020). The output of these phases is shown in Figure 4.5 one by one.

- In the first step, the Region Proposal Network (RPN) applies a classification algorithm to classify the objects in the image as background or foreground items. RPN additionally improves the suggested coordinates to fit the identified object better.
- The final proposals are grouped by type in the next phase, and their edge pixels are refined.
- A mask is generated for each image instance from phase two, which can be combined after it is applied pixel-by-pixel in phase three.

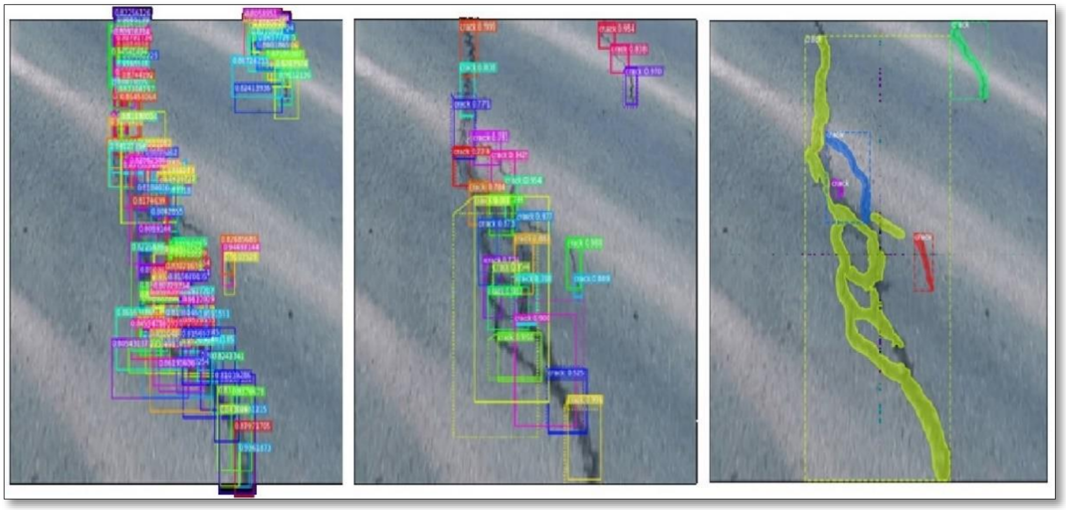

Figure 4.5 Mask R-CNN output for the three stages (left to right)[21]

4.4.3 Spatial data analysis

4.4.3.1 GIS module

Figure 4.6 depicts an overview of the data stream to the visualization step. The detailed step-by-step process will be explained in the following paragraphs.

[21] Source : ibid.

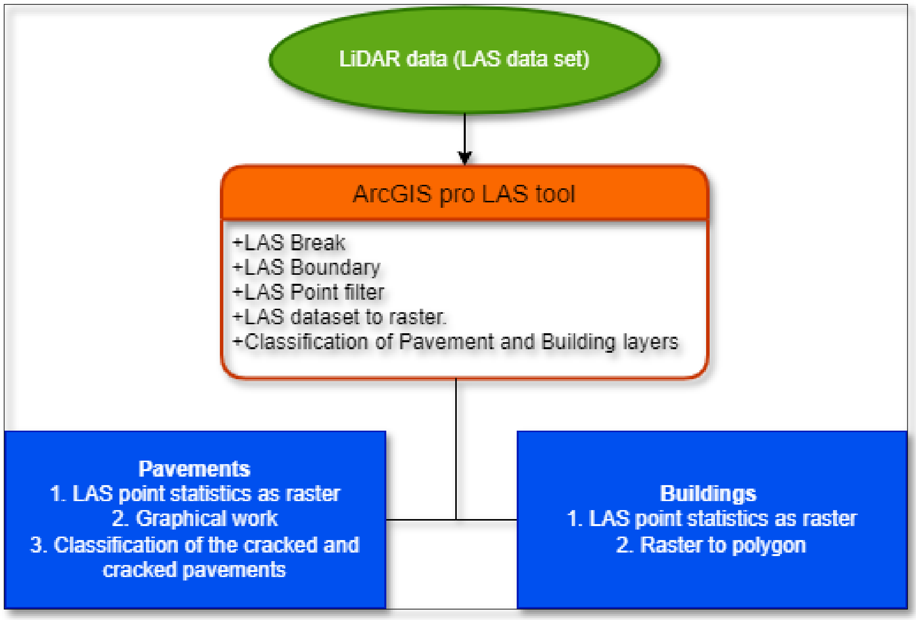

Figure 4.6 The analytical flowchart of the spatial analysis module

The LAS tool is an open-source toolkit for working with LiDAR files in ArcGIS Pro. LAS Break is used to split a LiDAR point cloud into a file that contains only road surface and building points that meet the criteria. The road surface and building footprint are then extracted using the LAS boundary. The LAS boundary program checks LiDAR data and creates a polygon border for the points. The input to LAS Boundary is a LiDAR point cloud comprising only road surface and building points, with Concavity set to 2 and the disjoint option checked. After importing the LAS dataset into the ArcGIS Pro software, all the noises were removed by the "LAS point filter" in the LAS dataset layer panel. Then, an accurate Digital Elevation Model (DEM) is needed, which is the base of all the analyses requiring height and 3D model construction. For this objective, the ground points are needed by filtering the data and extracting the ground points. By applying the "LAS dataset to Raster" option and selecting the interpolation type as "triangulation," which is more accurate and officially known, DEM would be created, as shown in Figure 4.7.

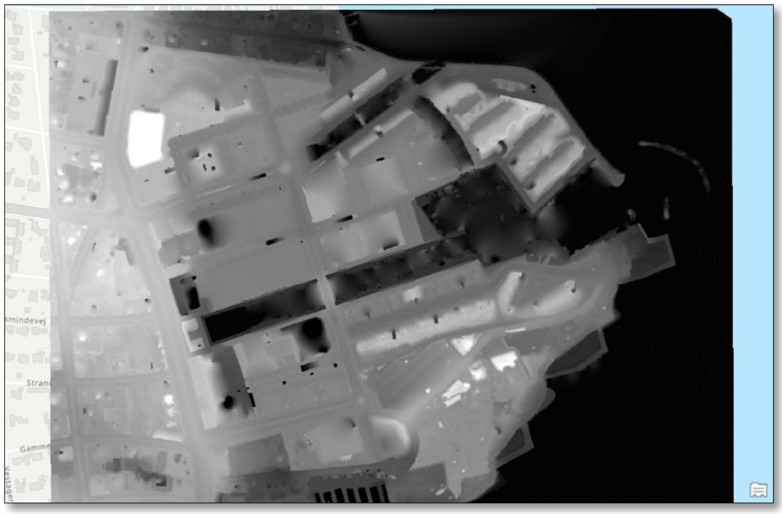

Figure 4.7 DEM extracted from ground point data

Classifying buildings and pavement locations is the next phase in the analysis procedure. The "Classify" analytic tool, accessible through the geoprocessing module, was used to classify buildings and pavement. The classification technique indicates whether places are classed as buildings and pavements accurately or not. Access to the minimum rooftop height and area limits is essential to guarantee that a surface that is too low or too small in the region is not mistakenly classified as a building.

It would be necessary to extract building and pavement footprints before moving on to the primary 3D model of this analysis stage, which would be the output of this step and imported straight into CityEngine to apply city officers' rules. Building footprints were extracted with the help of a simple tool in ArcGIS Pro called "LAS Point Statistics as Raster" and then "Raster to Polygon." On the other hand, Pavement polyline extraction is more complex and requires more investigation.

For pavement polyline extraction, first, it would be necessary to filter the LAS dataset and access the road points. Then, the appropriate raster would be prepared to run the LAS point statistics as a raster tool. Applying another tool to convert this raster to a polyline makes us move forward with the extraction of pavement polylines. However, some graphical works are needed to clean the feature class created and access the best appropriate shape of the pavements, as displayed in Figure 4.8. In addition, based on the crack detection phase, the pavement layer needs another classification step to differentiate cracked or non-cracked pavements. Therefore, this analysis is done, and from now on, all road sections are classified in terms of their crack inclusion. This classification is presented as an attribute value in the attribute table of the pavement layer.

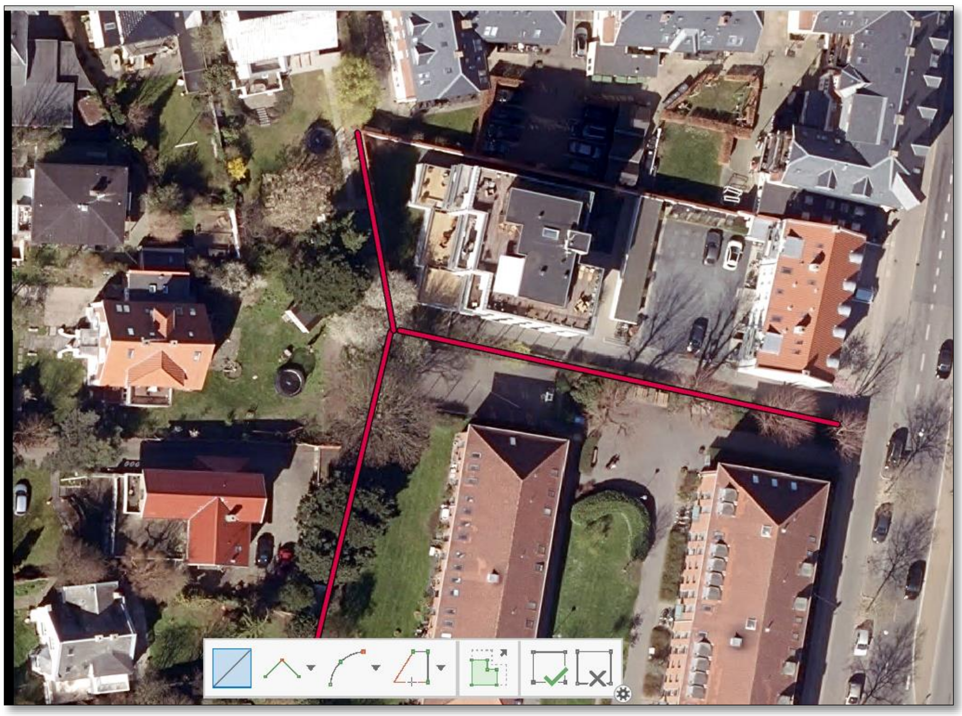

Figure 4.8 Pavement polyline extraction

4.4.3.2 AASHTOWare PMED

Since the objective of applying MEPDG in this study is to benefit from the excellent results of this design method compared with the rest of the same category, one of the recent MEPDG final reports of the study area is used. Providing the necessary data for a MEPDG requires time and money. As a result, and to show that getting the most efficient pavement design for the study area is either possible or beneficial in the SUIMS, the integration of the MEPDG final report and the analysis result of the GIS module was done accordingly. It means now the results help access the urban categorized road sections, which also have the current situation of cracked or non-cracked, and at the same time, they have their own best pavement design result.

4.4.4 3D city model rules and visualization

CityEngine supports several file formats for importing street polylines, depending on the data type. In this study, streets were imported as Shapefiles. Polylines that were put into CityEngine as street segments comprise the data. A width attribute, which determines street width in CityEngine, and another column indicating the presence of cracks are also included in the data ('0' means there is no crack, and '1' shows some cracks). The street network layer was generated automatically, and the Viewport showed street centerlines. Using the "Resolve Conflicting Shapes" tools in Cleanup Graph, various graphical disorders in the street centerlines shapefile are automatically corrected.

In this CityEngine configuration, the Computer Graphics and Applications (CGA) syntax defines streets and buildings. A CGA rule file is a collection of rules that define how geometry is created. A CGA rule file is usually allocated to a shape. The street model in this project was created using CGA from the Esri library.

4.5 Validation

Designing and building an intelligent pavement management system for urban road networks within the framework of a smart city involves several aspects that can be validated to ensure its effectiveness. Here are some key areas to consider for validation:

Performance Assessment: the system's ability to assess and monitor the performance of the pavement network is tested and reported accurately. This includes evaluating the accuracy of the system in identifying pavement distress, predicting deterioration, estimating remaining service life, and prioritizing maintenance and rehabilitation strategies.

Decision Support: the system's ability to provide decision support for infrastructure managers and stakeholders is tested and worked properly. This involves assessing the effectiveness of the system in generating actionable insights, recommending optimal maintenance and rehabilitation interventions, and optimizing resource allocation based on cost-effectiveness analysis.

Integration with Other Systems: the integration of the intelligent pavement management system with other smart city infrastructure systems, such as traffic management systems, public transportation systems, and emergency services tested.

Stakeholder Feedback: the system's usability and effectiveness through feedback from stakeholders, including infrastructure managers, road users, maintenance personnel, and other relevant parties reported positively.

4.6 Conclusion

Whether cities have substantial outdated systems or start from scratch, smart-city technologies help them get more out of their assets. Therefore, budget management is essential to prevent spending millions of dollars on physical assets and maintenance, but emerging technology can provide new capabilities as fundamental components are improved. The most up-to-date methods and software are used to monitor, measure, analyze, communicate, and act between pavements, a critical part of urban infrastructure.

Moving from the old-fashioned ways of managing urban infrastructure, which leads to a massive waste of money and time, is discussed in this paper. Applying the 3D mobile LiDAR and RBG cameras as the data collection tools is faster and more accurate. Since there is no need for the human interruption, it requires less calibration for post-processing analysis. Additionally, applying analysis tools like ArcGIS pro, PMED design, and CityEngine for spatial, pavement design, and visualization purposes helps city administrators access the most reliable data and analysis simultaneously.

The best advantage of this paper's finding on SUIMS is that it is applicable in different situations worldwide. Getting the support of CityEngine rules, on the one hand, and the capabilities of ArcGIS Pro and PMED design analysis tools, on the other hand, will empower all city officers to establish their objectives in the pavement design and maintenance procedure based on either their local or national sustainable development plans.

CHAPTER 5

BUILDING AR EXPERIENCE ON TOP OF A SMART PAVEMENT MANAGEMENT SYSTEM BY APPLYING CITYENGINE CAPABILITIES

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This chapter presents the paper published in the Buildings journal. This paper addresses the last research question and the third research objective and provides the AR visualization of the PMS in the study area. This paper answers how smart technologies like AR can help city managers decide on the best M&R solution for urban pavement rehabilitation before implementation. It has also achieved the third objective of the research, which was to investigate and weigh the benefits and drawbacks of incorporating AR technology into the planned framework to increase interaction opportunities significantly. This was accomplished by utilizing the geographic data accessible locally and saved in GIS platforms and services accessed remotely through applications, with an emphasis on building an AR experience on top of a smart PMS by utilizing CityEngine capabilities. This visualization is exclusive to this paper. A dynamic product that offers data and analysis and a DSS that end users can access in real-time is produced by integrating the CityEngine model and connected textures into the Unity game engine. Applying the suggested system to the case study revealed that it takes advantage of both the strengths of smart sensors and the rich graphical environment of AR.

Abstract

Pavement Management Systems (PMS) offer a systematic collection, storage, analysis, and modeling of road condition data to optimize resources across a road network. Adding artificial intelligence (AI) and augmented reality (AR) to PMS could improve their technical or visual aspects. This paper tries to identify a method to improve the understanding of the consequences of the city council's decisions in the urban pavement management system field. This paper establishes the potential of AR. It provides future maintenance and rehabilitation (M&R) actions needed based on the recommendation of the future distress in the study area. The road cracks are discovered through technical analysis, and a CityEngine model is established based on the PMS results. Additionally, in terms of visualization, this paper's unique feature delivers the result as an AR experience. Applying the Unity game engine and importing the built CityEngine model and the embedded textures as input empowered us to provide a dynamic product in terms of data and analysis and a real-time Decision Support System (DSS) for the final users. This paper concludes that researchers need many different modules to design and implement an efficient PMS to move toward a smart PMS. The smart city concept is meaningless without a tight collaboration between all distinctive parts of each urban infrastructure management system. Additionally, this paper attempts to provide answers for researchers and an outlook for future research, the development of the proposed method, and its application in other fields.

Keywords: intelligent pavement management, PMS, Urban infrastructure, AR.

5.1 Introduction

Roads connect more people and places, enabling economic growth and social development. Since the condition of road infrastructure impacts the citizen’s quality of life (Marović, 2013), every action should be carefully planned because this is a complex and sensitive issue. During the planning process, municipal governments, as well as all the road administrations, face significant challenges. As part of metropolitan plans, road infrastructure design and administration are critically crucial since construction, maintenance, and corrective action budgets must be identified each year (Jajac et al., 2015).

Road maintenance in cities was reactive in the past, focusing on repairing what was already in a bad state. The modern method is proactive and focused on maintaining a goal level of performance over time by protecting pavement assets that are still in decent shape. According to the proactive strategy, pavement management is an organized method of preserving, enhancing, and running a network of pavements (Johnson, 2009). The AASHTO (1993) defined the PMS as “a set of tools or methods that assist decision makers in finding the optimum strategies for providing, evaluating, and maintaining pavements in a serviceable condition over some time” (AASHTO, 1993).

The PMS can determine the right time for maintenance activities based on pavement distress indices and predictions. Moreover, pavement performance can be compared by pavement type, traffic volume, or other attributes. This information allows preventive maintenance programs to be developed, extending the life of pavements. Furthermore, it can simulate the budget requirements for maintaining pavement at various levels. However, there are still lots of obstacles to getting a smart PMS.

PMS is based on long-established monitoring methods that heavily rely on accumulated experience. In addition to updating PMS data collection methodologies and data analysis tools, technological advances like artificial intelligence (AI) and the IoT can be integrated into PMS decision support systems. With the help of intelligent technologies, we will be able to monitor and assess pavement conditions in a more effective, less expensive, safer, and environmentally friendly manner (Amândio et al., 2021). Due to the geospatial nature of every single element of a PMS, it is necessary to integrate the PMS and its visualization output with geographical information systems (GIS).

Developing a linear route system through GIS integration can enhance any PMS with pavement data. GIS can match the geographical characteristics of road networks using spatial analysis and is increasingly being integrated into PMS systems. The GIS-based PMS offers several advantages, including editing database queries, visualizing stats, and editing the database. Non-technical people will find it easier to understand a color-coded interactive 3D result. Answering the main research question, "What is the role of visualization technologies in the management of urban road infrastructure?" this study seeks to identify a method for improving the understanding of the consequences of city council decisions in a PMS based on an interactive visualization platform.

In 2016, when the industrial revolution shifted into a new phase (Schwab, 2017), AR emerged as the most important technical evolution. AR adds interactive virtual objects and pictures to real-world settings. Because AR is interactive and transparent, it offers a technical advantage over VR. In addition, AR in PMS can help avoid costly mistakes, increase efficiency, persuade municipal officials to make more efficient investments in urban infrastructure, and save money (Xu & Moreu, 2021). To move toward a smart city, including a brilliant PMS, game engines are being applied to build AR experiences. As an illustration, Figure 5.1 shows a simplified view of the AR experience in an urban area.

Figure 5.1 AR experience's schematic view[22]

To achieve this research's primary goal, based on AI and AR's capabilities, an intelligent PMS is elaborated on in this paper, and the results are presented. Our designed PMS's primary purpose is to clarify and brief the linked regulation to improve dealing with GIS datasets in PMS and produce an AR output of the planned PMS by combining accessible processes and

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[22] Source: Pascal Mueller, S. A. (2020). *Building VR/AR experiences with CityEngine, Unity and Unreal Engine 4*. Esri.

overcoming the traditional operation difficulties simultaneously. It also discusses how the final visualized output can help city officers and stakeholders prevent wasting millions of dollars annually by providing them a DT of the city pavements before implementing each PMS. The current work offers insights into how future DSS will help manage smart pavements. DSS of the future will need to be able to gather and analyze data from different angles, such as at the surface or inside a pavement, as well as detect and anticipate structural and functional defects for all types of pavements and visualize the smart PMS results in a way that is easily understandable by non-technical users. This paper relies on the monitoring of the condition of the pavement surface. While Traffic volume and distribution data, pavement characteristics and properties, pavement's spatial coordinates, and some other attribute data of the study area are essential parameters, the thesis considers them as attribute data in the PMS design phase.

This article is divided into five major sections: Section 5.2 provides a broad review of the literature, including PMS, AR, GIS, and their interrelationship. Section 5.3 consists of a methodology followed in this study to meet the objective of the research meet and fill out the research gap. Section 5.4 introduces the study area, defines the data used in this research, and the produced result is presented. The remainder of section 5.5 reviews the validation procedure applied in this paper. Finally, section 5.6 concludes the article and section 5.7 proposes future trends in the smart PMS and AR field.

5.2 Literature review

Due to the aging of pavements and degradation, which is amplified by the growing demand for infrastructure and growing traffic loads (Zagvozda et al., 2019), structured pavement management has become essential. Using GIS to improve pavement maintenance systems has been around for several years in various versions. University academics have used this strategy to study a few roads, often on campus (Al-hallaq, 2004; Ibraheem, 2012) or in partnership with municipal roadway agencies to establish a PMS for urban regions (Kiema & Mwangi, 2009; Kmetz, 2011; Lee et al., 1996; Picado-Santos et al., 2004). In North Carolina and Arizona, comparable systems were developed in collaboration with universities and implemented in some districts (Medina et al., 1999; Zhou et al., 2010). There are several GIS platforms that researchers work with to make their readers ensure that extent the produced results are accurate and reliable.

Several GIS software solutions for the design of such systems are mentioned in the literature, including ArcView (Ibraheem, 2012; Yunus & Hassan, 2010), Arc Info (Picado-Santos et al., 2004), MapInfo (Medina et al., 1999), ArcGIS (Ferreira & Duarte, 2005; Shrestha & Pradhananga, 2009), GeoMedia Pro (Jendia & Al Hallaq, 2015), and ESRI Map Objects (Morova et al., 2016; Tsai & Lai, 2002). These analyses can range in sophistication and plan for maintenance activities in the future. In addition to the GIS software, which focuses on geospatial data analysis, some PMS applications emphasize the technical aspects, like providing the optimum M&R solution for each road section.

Previously, pavement management solutions like HDM-III and PAVER are proposed (Watanatada et al., 1987). They depended on cost-benefit analysis and could not balance competing for asset types and traffic modes (Dowling, 2005). For asset management, most of these problems were solved by applying linear programming and other heuristic optimization methodologies (Chootinan et al., 2006; Robelin & Madanat, 2007). Route and connection options are influenced by traffic perception, road condition, route capacity, accessibility, cash benefits, physical security, and to a lesser extent, environmental responsibility. Adding more models to the PMS will improve its conceptual management and coherence with most economic expansion frameworks and make it more attractive to inexperienced users (Amin, 2015). The most comprehensive PMS includes a road dataset, a pavement condition evaluation method, and a decision-making device for maintenance costs and available resources (Picado-Santos et al., 2004).

Before starting the PMS implementation process, city agencies should assess the advantages, costs, and resources required. An assessment is needed for informed decision-making and public acceptance. Before alerting the public and elected officials about the benefits of PMS, each department must convey a cost-benefit analysis (Broten, 1997; Wolters et al., 2011). A PMS implementation's cost includes the initial setup and ongoing maintenance. The following are some of the factors that influence the cost of a PMS (Wolters et al., 2011):

- Collection of data and database creation,
- Obtaining and installing essential software,

- Staff training and consultant activities,
- Costs of pavement M&R.

Since quantifying all advantages and disadvantages may be challenging, an agency might do a fast study to determine the cost-effectiveness of deploying a PMS (Wolters et al., 2011). In the past, surface distress assessment data were collected either by walking along the shoulder (walking surveys) or by driving alongside its shoulder (riding surveys, also called windshield inspections) (Chin et al., 2019; Pérez-Acebo et al., 2018). These systems take a long time, require costly equipment, and may create traffic issues. Nevertheless, data are automatically collected, even for surface distress (Cao et al., 2020; Chu et al., 2022). In general, issues arise not because these techniques for monitoring pavement quality are less effective but because of the longer intervals between assessments, which decrease the total monitoring process performance and potentially affect decision-making. As a result, the DSS for pavement management's data collection and analysis procedures has room for growth (Amândio et al., 2021).

Data collection methods, as well as data processing methodologies, have an impact on the decisions made by these systems. Unmanned aerial vehicles (UAVs)(Outay et al., 2020), cars for research (cars embedded with sensors) (Nguyen et al., 2019), cellphones (Alavi & Buttlar, 2018), and sensors inserted in the pavement (Di Graziano et al., 2020; Schnebele et al., 2015; Shtayat et al., 2020) have all been studied by academics as innovative data collection methods for pavement monitoring.

On the other hand, a few pieces of research fill the gap between innovative data collection technologies and data analysis methodologies that are likewise based on novel intelligent systems and suited for inclusion in DSS for smart pavements. ML and other analysis technologies can extract meaningful information from this data, enabling pavement diagnosis and predictions. In addition, for a decision-making system, it is essential to have a relationship between the data and analysis section promptly.

The two recent studies have demonstrated the utility of linking data acquisition and analysis systems as a decision-making system for pavement management (Peraka & Biligiri, 2020) (Capotosto, 2021). However, their current evaluation process is primarily concerned with examining the pavement's operational state (i.e., surface distress identification and prediction or roughness indicator estimation), ignoring the possibility of a more complex DSS concept that includes developed tools for both structural and functional pavement monitoring (Amândio et al., 2021).

Figure 5.2 depicts a DSS covering smart cities' data collection mechanisms and functional and structural pavement metrics analysis capabilities. This diagram also shows how the two primary components of a DSS work together in an intelligent PMS: Methods of data collecting, as well as data analysis and decision-making tools (Amândio et al., 2021). Smart PMS are unlikely to succeed without citizens sharing information about events in the city, despite the existence of automatic systems for collecting data and making analyses. In addition to enabling users (including either city administration officers or citizens) to manipulate virtual objects in natural environments, AR can facilitate road management with significantly less time and expense.

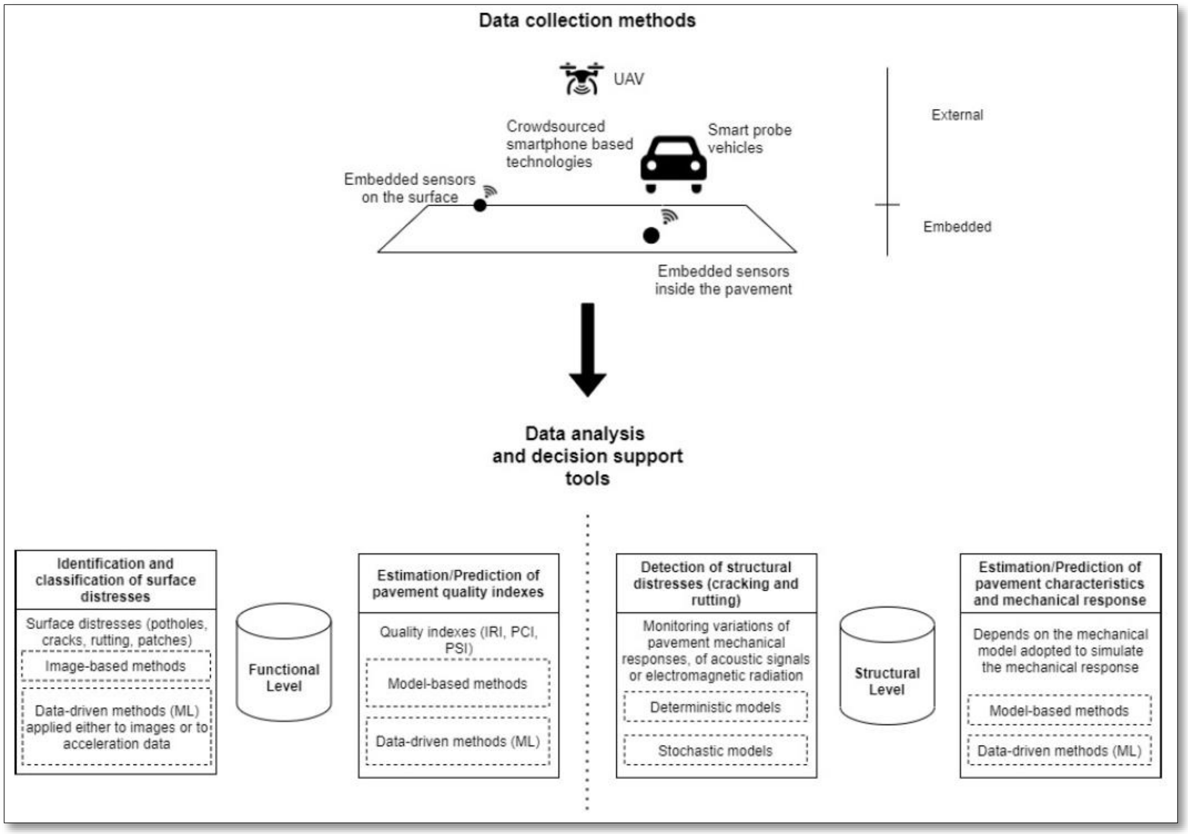

Figure 5.2 DSS for smart pavement[23]

The fourth industrial revolution has increased the implementation of AR in urban development studies. Figure 5.3 illustrates the number of research articles published ("Web of Science," 2020), indicating that interest in the AR field has grown since the fourth industrial revolution. AR has seen significant growth and implementation in civil infrastructure in recent years compared to its early years (Aoyama, 2019; Cattari et al., 2019; Petrillo et al., 2018; Thompson, 2019).

[23] Source: Amândio, M., Parente, M., Neves, J., & Fonseca, P. (2021). Integration of Smart Pavement Data with Decision Support Systems: A Systematic Review. *Buildings, 11*(12), 579.

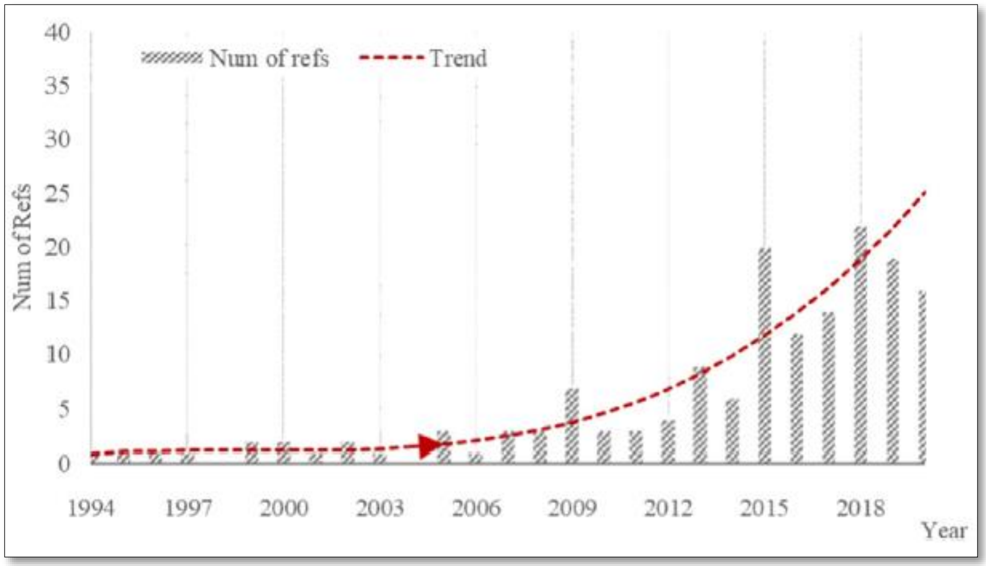

Figure 5.3 Civil infrastructure in AR deployment growth[24]

Based on the capabilities of game engines in producing AR experiences (Wang, Kim, et al., 2013), there are two main methods for AR applications categorization in civil infrastructure: by item (bridges, large structures, and rail lines) or by real applications (engineering layout, Structural Health Monitoring (SHM), structural design, manufacturing, and others) (Shin & Dunston, 2008). Figure 5.4 illustrates the proportion of AR applications in engineering structures from 2016 to 2020, broken into five categories: smart city, construction, BIM, SHM and damage detection, and subsurface utilities. The percentage is computed by dividing the number of articles into earlier periods by all the statistics of articles in the same period (Diao & Shih, 2019).

[24] Source: Xu, J., & Moreu, F. (2021). A Review of Augmented Reality Applications in Civil Infrastructure During the 4th Industrial Revolution. *Frontiers in Built Environment*, *7*, 640732.

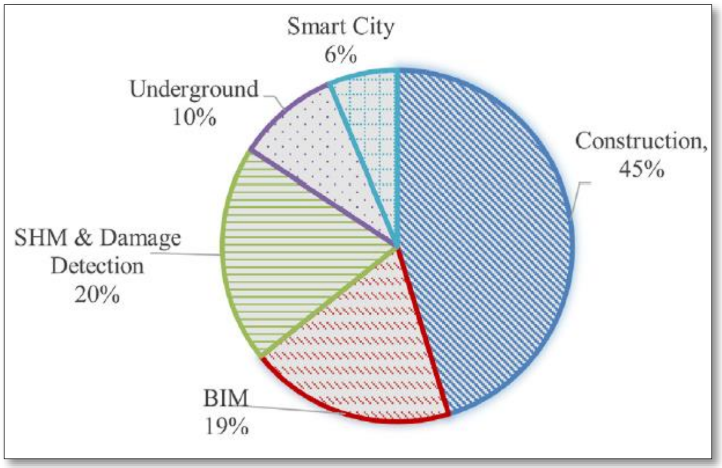

Figure 5.4 AR used in engineering structures[25]

Researchers should consider every specification when deciding on an appropriate AR platform (Jahn et al., 2019; Julier et al., 2004; Mahmood et al., 2018). In general, AR systems fall into two groups. The first is lab-developed prototypes, while the second is commercial AR gadgets on the market. A broad outline of AR applications in recent studies can be found in Table 5.1. Cities and stakeholders can test out changes before implementing them in the real-world using AR of real-world systems, places, or things based on DT.

[25] Source: Diao, P.-H., & Shih, N. (2019). Trends and Research Issues of Augmented Reality Studies in Architectural and Civil Engineering Education—A Review of Academic Journal Publications. *Applied Sciences*, *9*, 1840. https://doi.org/10.3390/app9091840

Table 5.1 AR deployments in civil infrastructure studies

AR application in civil infrastructure		Current progress		Technical/practical challenges	References
Architecture	Tracking Projets Development	Discrepancy check	Prototype devices and software have been developed.	Outdoor environment Occlusion problem	(Karsch et al.,2014)
	Quality control	Typical field implementations		Accuracy requirement Occlusion problem	(Zhou et al., 2017)
	Assisting workers	Collaborative Visualization	Theory	Communication stability	(Soman et al., 2017)
		Telecommunication	Experiments	Communication stability Occlusion problem	(Chi et al., 2012)
		Site safety	Experiments	Accuracy requirement Communication efficiency	(Liu et al., 2018)
BIM		Multiple prototype devices and software have been developed		Accuracy requirement Occlusion problem latency problem	(Machado, et al., 2020) (Dang et al., 2020)
Damage detection and SHM		Multiple prototype devices and software have been developed		Accuracy requirement Occlusion problem latency problem	(Xu et al., 2021) (Napolitano et al., 2019)
Underground utilities		Small-scale experiments		Localization problem. Accuracy requirement Occlusion problem	(Pereira et al., 2020) (Ortega et al., 2019)
Smart city		Concepts		Accuracy requirement Occlusion Problem Communication stability Privacy concern	(Woodward, 2015)

Based on a detailed review of the available literature, there is only one study about integrating AR technology with PMS. This study developed a mobile PMS on smartphones and a web-based PMS using Java programming language based on the location-based services concept. Mobile PMS allows road users and engineers to report road defects. To perform maintenance activities, the field road engineers view the reports on the web-based PMS. In addition to developing AR technology, the mobile PMS allows field road engineers to obtain immediate reports, plan routes and resources for neighboring defects, and perform maintenance on-site (Chang, 2011).

As it is thoroughly described, besides the only study done on the integration of PMS and AR technology in the framework of a PMS (Chang, 2011), there is no significant study that starts from data collection and produces a 3D visualized interactive result to move toward a smart city which is the most important research gap. Tackling this severe gap, this study aims to collect the appropriate spatial data, apply GIS and PMS analysis, and produce the result as an AR experience utilizing the unity game engine.

5.3 Methodology

The three critical steps of the planned PMS are depicted in Figure 5.5. Each phase will be discussed in detail in the following paragraphs.

Figure 5.5 PMS process flow chart[26]

[26] Source: Corporation, T. (2018). *City of Bloomington, IN Pavement Management Report*.

5.3.1 System configuration

The first step is creating a database with a GIS map and other pavement-related data. The designed PMS is based on a reliable database, and its reliability has a direct impact on future road status forecasting and M&R planning. Moreover, roadway data, traffic circumstances, pavement conditions, and all the essential expenses must be gathered for each street section. All obtained data is linked to the GIS map to establish the PMS GIS database. Creating an accurate GIS map takes a long time due to the amount of spatial analysis that must be evaluated and validated. Manual geocoding of information into a digital map may be required, as well as the collection and addition of additional roadway features.

Based on the requirements of the first phase, three-dimensional point clouds will be produced by the 3D LiDAR sensor covering the arterial roads of the study area. By minimizing the LiDAR field of view, the road surface can be obtained by removing data that is not relevant to the road surface. The areas will then be divided into frames on the road surface, each covering a section of the road.

5.3.2 Field data collection

The second phase entails the creation of road condition forecasts. Depending on the nature, number, and degree of distress, the system begins with identifying key condition indicators such as traffic loading data (vehicle/day), rainfall data, humidity data, etc. However, a pavement design system should be established to collect the research area's critical attribute data. Pavement design's primary purpose is to build a low-cost road surface that meets site-specific efficiency, service life, regulatory criteria, and the city manager's financial goals.

One of the essential pavement design considerations is traffic loading, including road congestion, load factors and distribution, tire pressures, and suspension system characteristics. Rainfall, humidity in the pavement layers, temperature changes, and defrost durations are all factors to consider. Pavement design is influenced by subgrade soil, moisture content, and other physical parameters (Kazmierowski, 2013). In this study, for this category of data, the data produced in recent research is used (Capotosto, 2021), which is partially presented in Table 5.2. The available data are as follows:

- Name, start and endpoint, length, width, and functional class of the roads,
- Traffic data (vehicle/day),
- Primary diagnosis of causes of deterioration,
- Tests and actions made by the public work department and cost of work,
- Cost to users (annual cost).

Table 5.2 Sample of the data[27]

Name of the street	Length (m)	Width (m)	Functional class	Estimated IRI (m/km)	Quality	Mesh cracks	Shore cracks	Longitudinal cracks	Ripples / Ruts	potholes
Major Street	38	7	Residential	6.0	90%	Mild. Opening 5mm or less	10%	Mild. Opening 5mm or less	----	----
Scott street	282	6	Residential	8.0	60%	Mild. Opening 5mm or less	20%	Mild. Opening 5mm or less	40%	Mild. Opening 5mm or less

The state of the pavement is assessed using a low-cost action camera that is utilized in conjunction with the LiDAR sensor on top of the automobile to collect pavement data (Figure 6 shows the overview of the camera configuration and equipment applied). Based on the information from (Tarabay, 2020), on arterial roads, video is recorded at a maximum speed of 40 km/h. Action cameras are famous for capturing action footage from the shooter's perspective because they are small and simple to set up. The camera is angled at a 40-degree angle toward the pavement. This design can collect a 4*3 square meters road section as a sample unit of pixels, meaning 1 pixel covers around 1 mm. Pavements in the exact location with similar features (for example, surface layer, traffic, and weather) should behave the same way. Estimating road conditions is commonly done by categorizing roadway sections into

[27] Source: Capotosto, L. (2021). *Développement d'une plateforme intégrée pour l'optimisation de la conception de la réhabilitation des chaussées* École de technologie supérieure]. Montreal.

families and developing a predictive model for each pavement group. Two categories of pavements are available: the first ones are the road sections with cracks and the second ones are without cracks. However, considering the cracks will not cover the whole road assessment, the rest of the pavement evaluation factors are not considered in this paper due to diminishing the model complexity. Furthermore, extracting building footprints is required for the research's last stage, which will result in a more thorough 3D city model.

5.3.3 Analysis and Reporting

In the third phase, expenses, long-term objectives, emphasized specific components, and budget limits are used to build M&R plans. To begin, it is necessary to determine M&R solutions and unit pricing for various pavement kinds. The organization can choose a timeline that aligns with its operational plans. When setting priority standards, evaluating the pavement quality, distress type, pavement performance, volume of traffic, and project record is necessary. Figure 5.6 illustrates the standard system to identify management strategies for M&R on a road network based on how they are developed. Specific performance measures that need to be met depending on city agency decisions are available that may be discussed through various scenarios.

In this study, four distinct management scenarios were used to illustrate how the quality of the pavement and related expenditures developed. "Do Nothing for 20 Years," "Pavement Condition Index (PCI[28]) Threshold at 60," "PCI Threshold at 70," and "PCI Threshold at 80" were the four options. These scenarios assessed the benefits and drawbacks of maintaining the network's pavement condition at a superior level and achieving the most significant lifetime extensions of the interventions. It could be a percentage above a performance criterion or an average pavement performance score.

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[28] An excellent pavement will have a PCI value of 100, with zero representing a failing pavement.

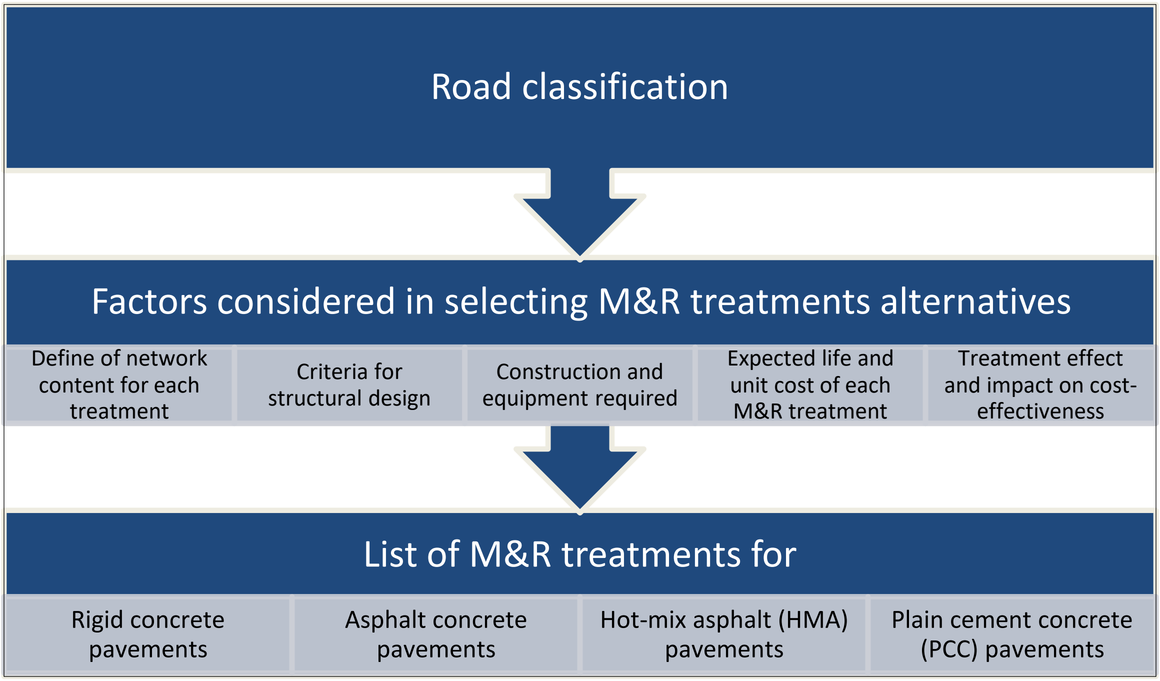

Figure 5.6 The process of developing practical M&R treatment strategies[29]

Having enough money to fix the road and satisfy those performance metrics will always be a difficulty, regardless of the objectives. The agency must determine the highest priority work projects and the optimal time to complete them to maximize the use of available funding. To provide the best visual output of the designed GIS-based PMS, it is necessary to display the results of the two primary phases in a 3D visualized platform.

However, providing the most understandable 3D city model to the stakeholders requires lots of data preparation and programming in a game engine. The produced model should also switch between different scenarios based on every stakeholder's priority.

Local and regional governments, financial investors, energy providers, ICT sector representatives, residents, government, property developers, non-profit organizations, planners, policymakers, specialists and scientists, political institutions, and media are

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[29] Source : Li, N., Kazmierowski, T., Tighe, S., & Haas, R. (2001). Integrating dynamic performance prediction models into pavement management maintenance and rehabilitation programs.

identified as critical internal and external stakeholders of an innovative city development project (Jayasena et al., 2019). Depending on the time and the location of each smart city project, the role of this vast category of stakeholders may vary a lot and impose different budget loads on the yearly planned budget for urban management.

Providing the optimum M&R treatment based on city stakeholders' priorities avoids wasting the financial resources of a city if it is presented and visualized in its best status. As a result, it is necessary to produce the CityEngine model before importing the model into the game engine because game engines are not still able to work with GIS data directly.

5.3.4 AR output visualization

The augmentation provided by AR in a smart pavement management system enhances the accessibility, visualization, and understanding of pavement-related information. It enables stakeholders to interact with the pavement system in a more intuitive and immersive manner, facilitating decision-making, maintenance planning, and public engagement.

As a visual overlay this type of AR involves overlaying visual information, such as pavement condition data, maintenance history, or future predictions, directly onto the real-world pavement surface. Users can view the pavement through a device, such as a smartphone or tablet, and see additional digital content superimposed on top of the physical pavement.

On top of the AR output of our designed model, the CityEngine model is needed for studying urban areas. Modeling an entire city can be done semi-automatically with CityEngine, a procedural generation tool. Using algorithmic or rule-based methods in procedural modeling allows the creation of large-scale scenes. It is possible to parametrize, control, or randomly set the rules that produce scenes (Ganster & Klein, 2007). Professionals in GIS, urban planning, architecture, multimedia modeling, and general 3D content production can benefit from CityEngine, which offers an effective solution for rapidly producing 3D cities and buildings. It is possible to create and modify as many scenarios as needed. From every viewpoint, facilities and street proposals can be analyzed and examined. It is clear how they tie into the broader vision for the city's future.

Based on these capabilities, in this step of the methodology, first, the result of data analysis acquired by the combination of the previous three phases will enter the CityEngine, and then considering the priorities of the city officers and macro-management policies that will be the criterion in each executive project, the appropriate rules would be applied (the details are depicted in the Figure 5.7). Formerly, for the visualization goal, a three-dimensional model will be prepared and imported to the Unity game engine of the designed AR experience.

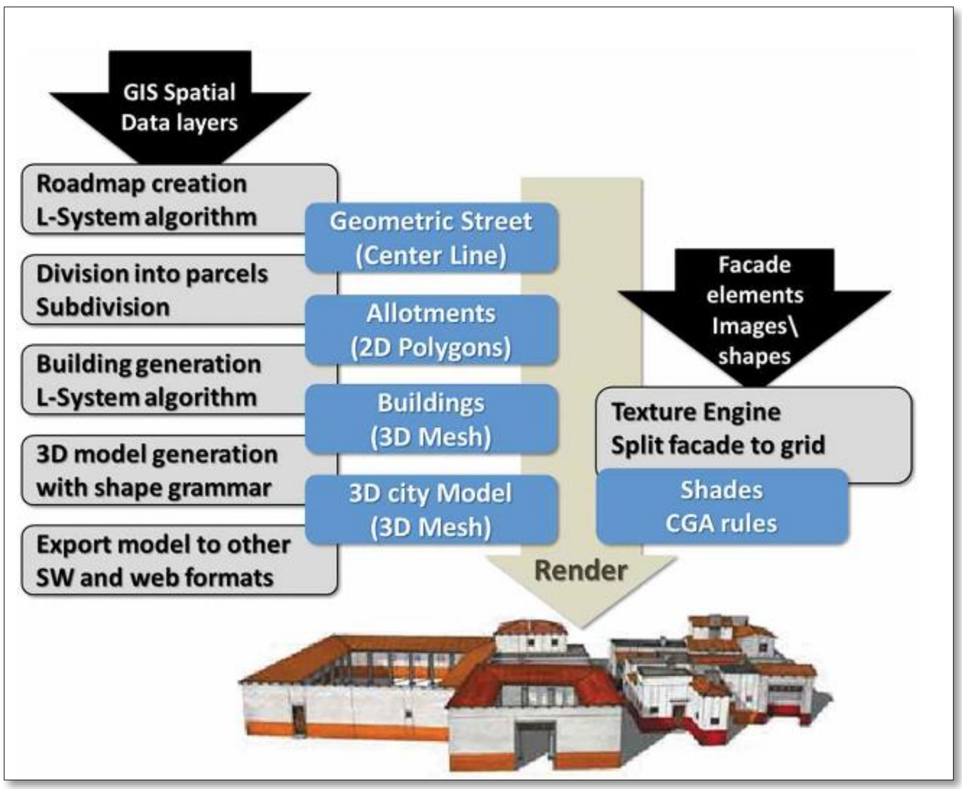

Figure 5.7 CityEngine step-by-step procedure[30]

[30] Source: Badwi, I. M., Ellaithy, H. M., & Youssef, H. E. (2022). 3D-GIS Parametric Modelling for Virtual Urban Simulation Using CityEngine. *Annals of GIS*, 1-17.

City managers can predict results and develop a more sustainable city by making mistakes and testing scenarios in the digital version of the city pavements. As a result, DT could interface with real-time pavement data, enabling us to regulate critical services and activities. Therefore, collaboration with game engines is required to create AR experiences for the study area roads. This paper applies the Unity game engine to generate the necessary AR experience. Some characteristics of Unity are as follows:

- It has a complete game development environment,
- It runs on all major platforms and supports many target platforms (PC, mobile, console),
- It supports state-of-the-art 3D rendering.

For GIS and CAD data, Unity still has some restrictions. It works in a local coordinate system and cannot deal with georeferenced systems, which is the most unpleasant key factor. In a georeferenced system, a digital map or aerial photo's internal coordinate system can be related to a ground system of coordinates, and the most critical data entered the analysis model. Due to the importance of having access to the correct spatial georeferenced data, it must be converted (centered) before being imported into Unity. It should also be noted that the extent must be limited depending on the base unit used. Unity concentrates on rendering (with certain modifications, such as collisions) and optimizes (e.g., combine) geometry so it can be batch-rendered. As a result, formerly organized data becomes unstructured, making it difficult to engage.

Data preparation is needed to overcome the limitations of importing the CityEngine model into the Unity game engine. This step is a new term. It is done within the game engine, namely, transforming the data. Hence, it fits the engine, which means hooking it into the game engine and importing the process to filter, optimize, replace, and enrich the data are possible. In Unity, custom imports, scripts, and FBX models are used. FBX is a proprietary format for exchanging 3D geometry with Autodesk's freely available Software Development Kit (SDK). Access through the Unity game engine is now the leading exchange format for AR/VR applications and game engines. The FBX model is the output of the CityEngine which will be imported here for the rest of the process. A data flow graph can be built visually and says what is needed to do with the data which has been imported. Figure 5.8 represents the view of Unity in the data preparation step.

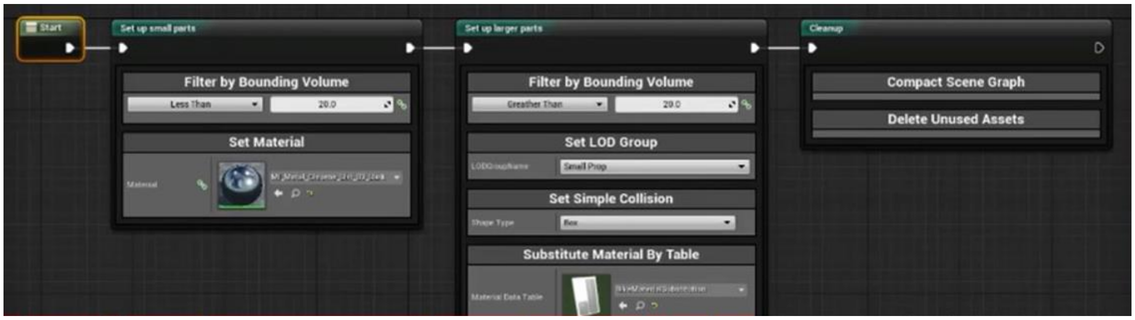

Figure 5.8 Unity data preparation view

Until now, the only way to obtain geographic data in Unity was to use CityEngine, which has much connectivity for importing this type of data. For the methodology (depicted in Figure 5.9), it can be imported:

- BIM/CAD models using FBX data type,
- Base maps through the get map data mechanism,
- Synchronizing the data from ArcGIS Online and ArcGIS urban platforms.

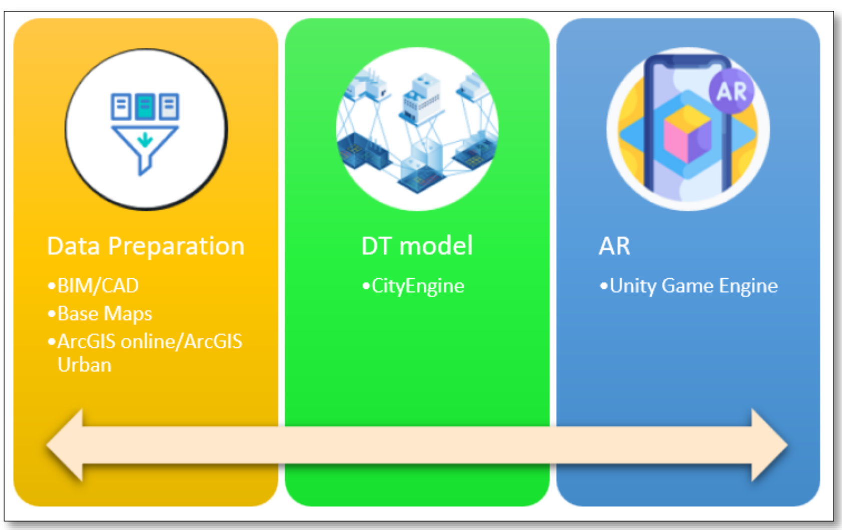

Figure 5.9 Data to information flow in the AR experience

Building the scene in Unity, moving the camera to a place of interest in the study area, focusing on each road part, adding features to the desired road section, and replacing CityEngine preview materials with high-quality Unity texture material would be the final steps. This would result in a reliable visual and interactive 3D image of the road section and a real-time analysis of the proposed PMS's ideal scenario. The results will be presented in section 5.4.

5.4 Results

Based on the methodology elaborated in section 3, the rest of this section will provide a detailed step-by-step procedure of the implementation phase of this paper, including the study area presentation, data and model applied, and finally, the AR experience produced.

5.4.1 Study area

According to the 2021 census, the City of Châteauguay is a small to medium-sized city in the Canadian province of Québec. It has 50,815 residents, a 500-kilometer road network, and a replacement value of around $1 billion. Both residential and industrial growth are occurring quickly. Pavement deterioration happens faster than expected because of an older network, higher traffic, and multiple routes. Like other Canadian towns, the issue is that the annual budget is insufficient to maintain these constantly deteriorating roads to an acceptable level, creating a huge backlog of M&R work that must either be completed as soon as possible or postponed at a higher cost. Therefore, it is crucial to have a solid, dependable, and easy-to-implement PMS that is founded on the following features:

- Trustworthy data,
- Identifying the cause of the deterioration,
- This is confirmed through relevant testing and the selection of actions that can address the deterioration's cause,
- A cost-benefit analysis of the life cycle,

- A visualized AR experience based on a real-time scenario to persuade city officers to invest in an interactive and intelligent PMS.

5.4.2 Data

The PMS is applied to the city of Châteauguay's pavements by gathering all essential data from the existing research (Capotosto, 2021; Tarabay, 2020), integrating it, and creating the most comprehensive GIS database. Traffic data (vehicle/day), comfort index and estimated IRI, cost of work, the cost to users (annual cost), internal performance street names, lane type, primary diagnosis of causes of deterioration for each road section, tests and actions taken by the public works department are all included in the attribute table of streets. A polygon represents the geometry of the building footprint data. Building footprints have three attributes: building type, building height, and the number of floors.

It would be necessary to extract building and pavement footprints before moving on to the primary 3D model of this analysis stage. Building footprints may be extracted with the help of a simple tool in ArcGIS Pro called "LAS Point Statistics As Raster" and then "Raster to Polygon." On the other hand, Pavement polyline extraction is more complex and requires more investigation.

For pavement polyline extraction, first, it would be necessary to filter the LiDAR point cloud (LAS) dataset and access the road points. Then, the appropriate raster would be prepared for the LAS point statistics as a raster tool. Applying another tool to convert this raster to a polyline makes us move forward with the extraction of pavement polylines. However, some graphical works are needed to clean the feature class created and access the best appropriate geometrical shape of the pavements.

5.4.3 Creating the CityEngine model

In this study, streets were imported as Shapefiles. Polylines that were put into CityEngine as street segments comprise the data. The street network layer was generated automatically, and the Viewport showed street centerlines. Using the "Resolve Conflicting Shapes" tools in Cleanup Graph, various graphical disorders in the street centerlines shapefile are automatically corrected.

In this CityEngine configuration, the Computer Graphics and Applications (CGA) syntax defines streets and buildings. A CGA rule file is a collection of rules that define how geometry is created. A CGA rule file is usually allocated to a shape. The street model in this project was created using CGA from the Esri library. The Essential Street CGA file includes screen resolution, road network, side configuration, parking design, bike lanes, landscaping, street items, and population.

It should be noted that because the GIS database includes all the different attributes of a single road section, the created city model encompasses those data. Figure 5.10 shows that all the data is presented by clicking on every single part of the city pavements.

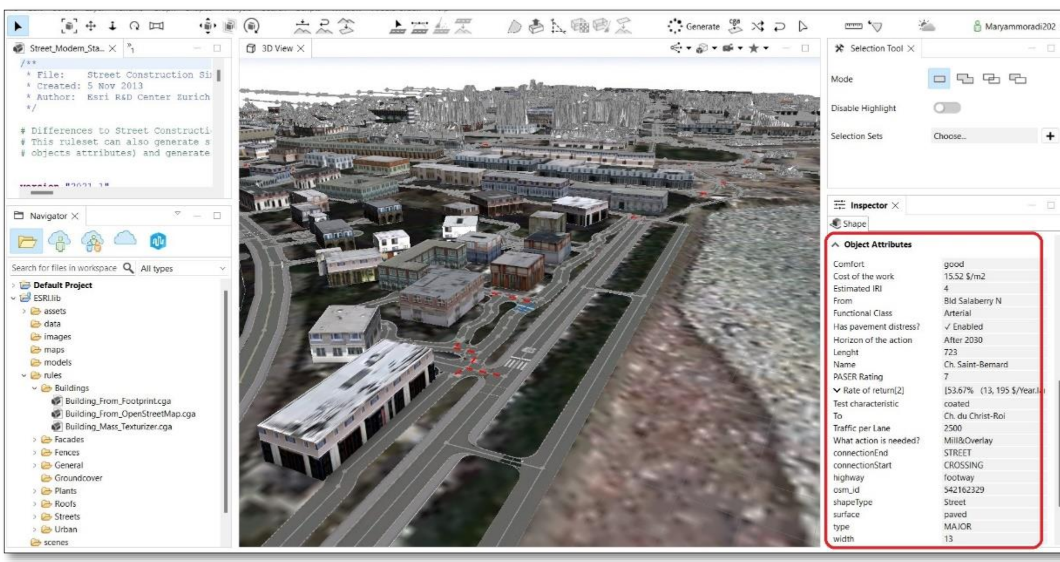

Figure 5.10 CityEngine model of the designed PMS

Later, to be able to apply the generated model in the Unity game engine, it is necessary to export the model as an Autodesk FBX model. Figure 5.11 shows the details.

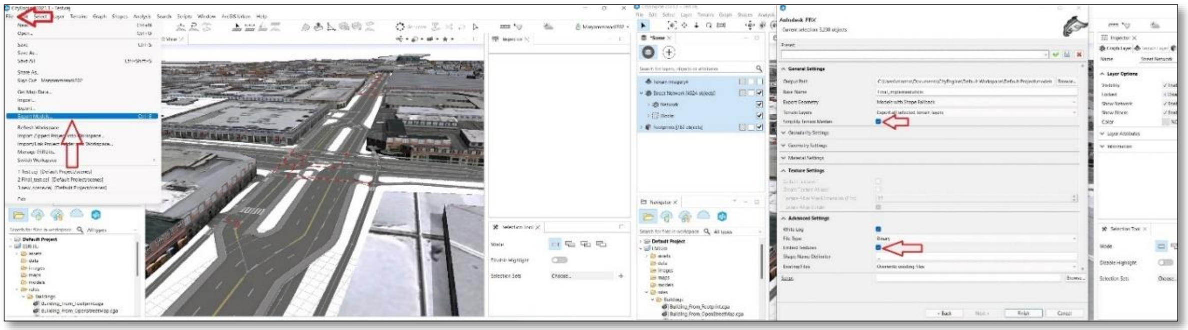

Figure 5.11 Details of the Autodesk FBX model settings

5.4.4 AR experience

After dragging and dropping the FBX model into Unity, the camera must be moved to a study area point of interest. It would only be the beginning of developing the AR experience, including adding AR extensions via AR camera motion controllers and a slew of other features depending on research requirements. It would then be feasible to play around with the created AR experience from the point when the camera is positioned on it before adding the features by pressing the "Play" button on top of the screen (Figure 5.12 shows how it can be played to move around the built AR experience).

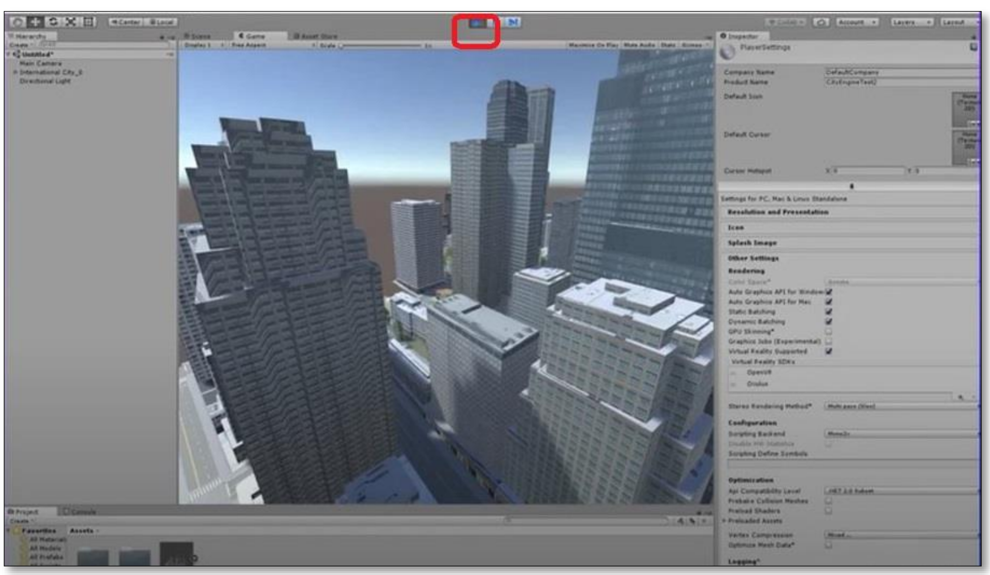

Figure 5.12 Playing the AR experience built based on the designed PMS

5.5 Validation

In this paper, the triangulation method was used to validate the study system because of the integration of different technologies applied to produce the final 3D AR experience of the study region. Using triangulation can cross-verify methodologies from more than two sources to validate it. Using a variety of instruments allows us to assess the consistency of the results and identify any factors that might influence them adversely.

By combining several techniques or sources of data, triangulation is utilized to create a more thorough knowledge of events (Patton, 1999). According to two excellent recent research pieces, there are four diverse types of triangulation: data, investigator, theory, and methodology triangulation (Denzin, 1973) (Patton, 1999).

Practicing employing three separate data sources to boost a study's reliability is common. The expert interviews' responses would be reviewed throughout the analysis to identify areas of agreement and disagreement. Categorizing each stakeholder group for the program, we are evaluating is a crucial strategy. It also ensures that an equal number of stakeholders represent each stakeholder group.

Here in this paper, we applied data triangulation. To get the opinion of the desired stakeholders, we asked a group of urban municipal experts and citizens in the study area to participate in the validation process. Tables 5.3 and 5.4 are two sample questionnaires to endorse the system. It should be mentioned that before filling out the questionnaire, the plan was presented in detail to them.

Table 5.3 First sample of the validation Questionnaire

	Low	Medium	High
What was the quality of the implementation system?			
To what extent were the program objectives met?			

Table 5.4 Second sample of the validation Questionnaire

What other impacts did this system have?	
How could the system be improved?	

The validity is established based on the results acquired in this step. Due to the different stakeholder groups involved in the system, this type of triangulation is the most popular and efficient one in the integrated framework containing different technologies (The framework of the triangulation validation method for this paper is displayed in Figure 5.13).

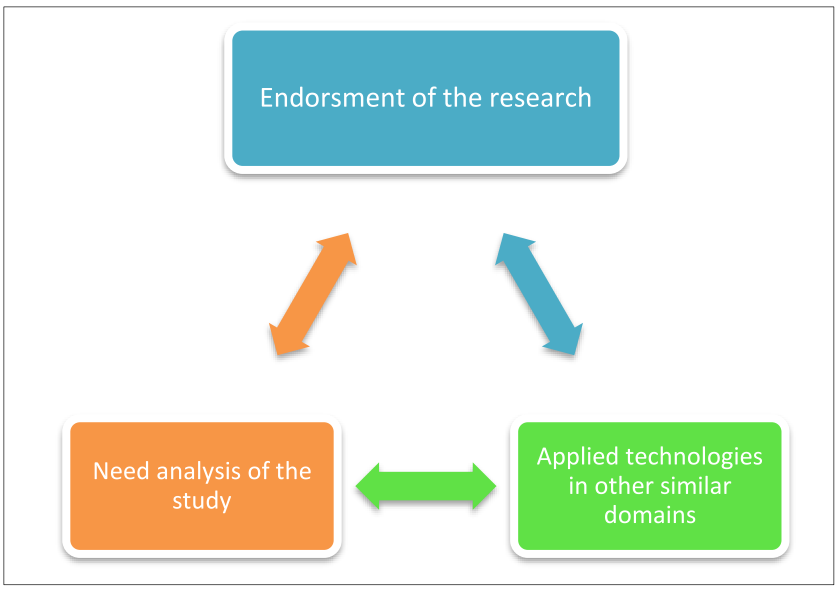

Figure 5.13 Triangulation schema

As a sample of responses to the designed questionnaire, the quality of the implementation system was high. The system successfully integrated CityEngine capabilities with the smart pavement management system, allowing for the creation of an AR experience. The implementation was technically sound, providing seamless interaction between the virtual AR elements and the real-world pavement data.

The program objectives were largely met. The paper aimed to enhance the user experience and decision-making process in the pavement management system by integrating AR technology. The implemented system effectively provided a visually immersive AR experience, allowing users to overlay pavement condition information and analytics onto the real-world environment. The integration of CityEngine capabilities contributed to achieving the desired objectives.

In addition to achieving the program objectives, this system had several other impacts. Firstly, it enhanced the accessibility and understanding of pavement condition data by providing a user-friendly and interactive AR interface. This allowed stakeholders, such as infrastructure managers and decision-makers, to gain valuable insights and make informed decisions regarding pavement maintenance and rehabilitation. Secondly, the system fostered public engagement and awareness by offering a novel way for the public to interact with and understand the importance of pavement management in the context of a smart city.

While the implemented system demonstrated significant advancements, there are areas for improvement. Firstly, expanding the system's capabilities to support real-time data updates would enhance its relevance and applicability. This could involve integrating live data feeds from sensors or crowdsourcing platforms to ensure up-to-date pavement condition information. Secondly, incorporating additional AR features, such as predictive modeling or simulation of future pavement deterioration, would further empower users in making proactive maintenance decisions. Lastly, considering the scalability and compatibility of the system with different devices and platforms would ensure broader accessibility and usability for a wider user base.

5.6 Conclusions

This paper reports on innovative developments in infrastructure monitoring that can help create intelligent pavement maintenance in urban areas and save money for taxpayers. To do this, the process begins by determining why the PMS requires using contemporary innovative technologies and AI-based platforms. The PMS was then divided into three main phases. Because the significance of comprehensive GIS data and analysis in urban infrastructure studies is particularly essential, the research technique applies data from the city of Châteauguay's pavement network to obtain the most reliable data. Since creating the AR experience in urban infrastructure research plays a colorful role nowadays, and almost no research has been found focusing on this framework, this paper concentrated on building the CityEngine model of the study area on top of the designed and implemented AR experience. It has been proven that game engines are practical tools to depict city agencies' essential needs in terms of technical or fiscal management strategies in an interactive platform. So, the Unity game engine is applied in this paper to prepare the most comprehensive vision of the study area PMS before implementation.

The results of the designed system and the framework's verification by two stakeholders satisfy the paper's primary objective. By providing stakeholders with DTs of the city pavements before the implementation of each PMS, the final visualized output can prevent millions of dollars in waste every year. This paper concludes that although linking spatial data and game engines is still impossible without middleware, the future of PMS and intelligent cities is unimaginable by neglecting the role of 3D visualization platforms, including AR environments.

5.7 Future trends

Intelligent data acquisition and assessment systems for functional and structural evaluations may help future DSS for road maintenance. Compared with conventional methods and research methodologies, this integrated strategy could save money and resources while improving the efficacy of infrastructure institutions' maintenance and monitoring programs. It must derive insights at multiple levels, both on the surface and within the pavement, and identify and forecast all forms of structural and functional faults and flaws as part of a coordinated DSS. Close collaboration between civil and IT specialists is also required to establish a comprehensive framework that encompasses all smart technologies in their DSS.

CONCLUSION

In today's world, besides the advances of innovative city management in virtual environments, it is evident that having the DT, including an interactive PMS, is essential and helps city decision-makers representing the stakeholders or any citizen to a better way of the urban management. The development of a simplified system for pavement management at the city level is based on a literature assessment of the latest technological advancements in urban infrastructure maintenance, including IoT, GIS, CIM, and AR. The thesis offered a solution for the city's road management system in Châteauguay, Québec, Canada.

Considering the context of a smart city and its related urban infrastructure management system, this thesis concludes that making a comprehensive smart PMS and applying the recently emerged cutting edged technologies to overcome the previous issues is a necessity in the intelligent city concept among researchers. Although there are many examples of smart PMS run up to now, no significant study developed a system starting from data collection using IoT and ending in a 3D interactive visualized platform accordingly, which is the most significant contribution of this study.

The result of the thesis meets the objectives defined earlier. Following the first objective and Table 6.1, SUIMS are technological systems that manage all public works operations on a single platform. The efficacy of decisions made by city officers and stakeholders can be increased with the appropriate selection and application of SUIMS. SUIMS covers a variety of procedures, including asset inventory and data collection, asset inspection, and performance data collection, asset maintenance, financial asset management, DSS, and finally, data visualization for each category of infrastructure assets. The SUIMS designed explicitly for managing urban pavements in this thesis is a subclass of municipal integrated infrastructure asset management systems (i.e., roads and pavements).

Table 6.1 four different modules of SUIMS

Asset inventory and maintenance management module (1)	Asset inventory and data collection	Asset performance modeling module (2)	Asset deterioration forecasting functions	DSS module (3)	Decision scenario generator	Intelligence and reporting module (4)	Interactive data postprocessing and visualization tools
	Asset inspection and maintenance management				Optimizer (solver)		
	GIS						

The developed methods for detecting road cracks based on manual and automated inspection of urban pavements, such as 2D image processing and 3D reconstruction, are discussed in the thesis' second objective. The literature review demonstrates the limitations of these methodologies. While some of these techniques are surprisingly good at detecting surface distress, their regular deployment is prohibitively expensive to scan and evaluate pavement deterioration. In terms of asset inventory and data collection, the 3D LiDAR data is first assessed to see how well it can identify road cracks. According to the results, the current 3D spinning LiDAR technology used in self-driving cars has poor precision. Crack detection using RGB images and a region-based deep CNN are also investigated and provided the most optimum technical or financial results, making the future application of the designed system more efficient. This capability is another outstanding contribution of this research, making it more useful for municipalities and policymakers.

When the data collection and crack detection are done in the asset inventory and maintenance management module of the system, then it is time to switch to the asset performance modeling module. In this module, the performance of infrastructure assets is predicted over time using performance functions relevant to each road segment. These tools simulate the behavior of pavements while considering a variety of variables, including temperature, usage scenarios, and maintenance procedures (i.e., do-nothing, routine maintenance, etc.) which is the third module called DSS.

Following the third objective and the last module of Table 6-1, this thesis visualized geospatial data of urban road pavements. This thesis's remarkable feature shows the DSS's result based on the city officers' and stakeholders' priorities. There is almost no study in the field of SUIMS which considers the incredible capability of AR in visualizing the PMS results. Showing the results of different scenarios in advance of each PMS implementation in an interactive environment will prevent wasting millions of dollars every year on each municipality's financial program.

Even though the tried solutions have some excellent results, security, privacy, and interoperability remain significant obstacles to IoT adoption. The integration of IoT technology with CIM and GIS has the potential to improve smart PMS significantly. IoT is still in its initial stages of development, although CIM and GIS technologies have matured. However, the heterogeneity of the IoT sensors is a challenge in road maintenance programs.

The AR experience is complicated by the convergence of GIS and AR technology. Due to the current state of development of AR geolocation systems, the positioning of the virtual objects may not be correct. The system could place one infrastructure in the wrong place or even next to another. These issues lead to a poor user experience while using AR environments. As a signal of the limitations of this section, it should be emphasized that working with geospatial data is not supported inside the game engines as of now. It means all the spatial analysis should be done before entering the AR environment. These limitations make converting the data into 3D information inside the AR experience more time-consuming and, as a result, more expensive. By overcoming the stated limit, there would be no need to get the help of third-party platforms such as CityEngine as an interface between GIS and AR.

IoT and AR technology integration issues may have several characteristics. The AR environment will provide wrong information about the road infrastructures if the IoT sensors gather false data. The predicted profits of the municipal administrators and stakeholders must therefore be balanced against the reliability of the capabilities.

RECOMMENDATIONS

The results of this study could be very advantageous for both industry and academia. The suggested strategy might address future research breakthroughs. However, the study had specific issues that may be fixed to produce more accurate findings. A list of research limitations and potential research fields will be as follows:

1. An application of the designed system will be encouraged if more case studies are used. Therefore, applying the new methodology to more case studies, such as field research or laboratory tests, will be interesting. This application will verify the usefulness and efficiency of the proposed system.
2. The case study is constructed based on the literature of another study and is somehow challenging. Systems and their functions are simplified. Hence, the boundaries of the PMS function characteristics and designs can be better identified with more detail for the rest of the case studies.
3. The proposed system is based on the data of LiDAR sensors as the data collection tool. LiDAR sensors, besides providing a lot of efficient data, have cons. Applying other sensors that can connect with the rest of the framework on a real-time basis can result in a faster stream of data for information production.
4. The preprocessing of geographical data before being entered into the game engine requires several steps, and the data must be centered before it can be loaded. This issue will be addressed by software developers shortly since the application of game engines in spatial analysis is progressing quickly.
5. Since pavement deterioration is still impossible to depict graphically in an AR environment, it presents the output in tables, with access to attribute data available by selecting each road section. The need for graphical visualization of current road conditions, including all existing deteriorations, is high among city managers who are not GIS experts. IT researchers should also address this as the need to expand intelligent cities, and their by-products are very high-demanded these days.

6. As there is almost no research before this, considering the integration of the intelligent technologies applied in this thesis, there would be no quantitative way to validate the result. Discussing and providing more research results in such a study area is needed.

ANNEX I ACADEMIC ACCOMPLISHMENTS

Journal Articles

1- **Submitted**
   Maryam Moradi, Gabriel J. Assaf, Intelligent management architecture of urban infrastructure, Scintia Iranica Journal, October2022.

2- **Published**
   Maryam Moradi, Gabriel J. Assaf, Building AR experience on top of a smart pavement management system by applying CityEngine capabilities, Budlings Journal, December 2022.

   Maryam Moradi, Gabriel J. Assaf, Designing and Building an Intelligent Pavement Management System for Urban Road Networks, Sustainability Journal, January 2023.

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