POLITECNICO DI TORINO

Department of Structural, Geotechnical and Building Engineering

Master of Science

LM-24 Building Engineering – Green Building

A Literature-Informed, Stakeholder-Driven Proposal for Tunnel Asset Management: Integrating GIS and Sensor Monitoring

Supervisor

Assoc. Prof. Valentina Villa

Candidate

Diana Lamaj

March, 2025

Thesis Structure

*To the greatest love of my life, to my hope, to **Umut**.*

AKNOWLEDGEMENTS

The decision to leave Istanbul behind and move to Turin was the most difficult one I have ever made in my life so far. But I had a dream, and I was determined to follow it no matter what—I wanted to study Green Building at all costs. My love, life, and happiness were being challenged, and without the support, patience, and dedication of my dearest Umut, I would never have embarked on this journey. My deepest gratitude goes to him.

I would like to thank my two sisters, Ari and Ruku, for brightening my lonely days with their presence and for always believing in me.

To my mom and dad, I am forever grateful for instilling in me a love for education.

A heartfelt thank you to my best friends, who have stood by my side for years—without them, I would not be the Diana I have grown to be.

To the family I have built in Turin and the beautiful people I have met along the way, thank you for transforming this city's climate and making it feel warm.

I am immensely grateful to all my lecturers at PoliTO, especially my thesis advisor, for their inspirational lectures and invaluable conversations.

To everyone who, in one way or another, has touched my life and left a mark—whether big or small—thank you.

Finally, I thank the Universe and God for aligning the pieces and helping me make my dream come true.

And last but not least, I thank myself— for yielding but never fracturing.

ABSTRACT

The management of infrastructure assets is essential for ensuring the safety, durability, and efficiency of transportation networks. There is an increasing tendency to integrate traditional Asset Management (AM) with developing technologies to enhance maintenance strategies, better safety measures, and optimize decision-making processes. Tunnel Asset Management (TAM) as part of the broader framework of Infrastructure Asset Management (IAM) is being revolutionized by the ever-increasing interoperability of innovative solutions such as Internet of Things (IoT) systems, Geographic Information Systems (GIS), and Building Information Modeling (BIM) in the way asset data is collected, analysed, and utilized.

A comprehensive literature review of the state-of-the-art of TAM served as the genesis for the workflow identification of the final proposal that this thesis aims to give. The thesis explores how real-time data collection can be connected to GIS software and display continuously the assets' state, enhancing the decision-making-related process. For this thesis, it was used ArcGIS Pro software to visualize a selected portion of a tunnel located in Liguria, Italy, and an IoT-based sensor technology connection to it to analyse live readings of 4 parameters: temperature, humidity, structural vibrations, and CO levels. By adopting this proposal, stakeholders can use real-time tunnel data with GIS technology to enhance monitoring and improve overall asset management practices. This approach can be highly effective in addressing important challenges within TAM, such as the optimization of maintenance schedules, early detection of any hazards, and enhanced stakeholder communication. By the development of a Dashboard for the final data visualization, it highlights the future prospects of IoT and GIS regarding the revolutionization of asset management practices by providing user-friendly, accurate, and actionable information.

The proposal examines its strengths and limitations and offers recommendations and the potential for future work in the field, applicable in various categories of assets. Ongoing development in technologies and interoperability holds the power to further enhance the capabilities of TAM, contributing to an infrastructure that accounts for the times of climate change and is sustainable and resilient.

Keywords: IAM, TAM, GIS, Real-time Monitoring, Sensor Technology, ArcGIS Pro, Interoperability, Data Visualization, Stakeholder Communication, Maintenance Optimization, Decision-making Processes, Sustainable Infrastructure, Resilience

SUMMARY

Chapter I – This chapter introduces Infrastructure Asset Management (IAM) as a multidisciplinary field aimed at optimizing infrastructure performance, reducing costs, and managing risks. Standalone technologies supporting IAM such as GIS, BIM and IoT together enable sophisticated data integration and enhanced decision-making abilities. Prompted by present global infrastructure related incidents, the thesis investigates the shortcoming of outdated systems and proposes a GIS-based dashboard to real-time tunnel monitoring with the help of installed sensors. Some of the most important goals of the proposal are to centralize data, facilitate preventive maintenance while delivering a user-friendly interface for the stakeholders. The methodology combines a systematic literature review which serves as the base of the innovative approach to improve tunnel, and not only, asset management.

Chapter II – The 2nd chapter is the most important one in terms of content that represents in the scope of the literature review. A detailed analysis of the key theoretical concepts upon which the thesis is built can be accessed here: Infrastructure Asset Management (IAM), and then a particular focus on Tunnel Asset Management (TAM). The chapter explores the theoretical background of risk management and resilience in transportation infrastructure and the relation that exists with the current climate changes and global trends. Then it proceeds by highlighting the importance of interoperability of various technologies such as: BIM, GIS, IoT. These technologies are fundamental for better monitoring, enhanced decision-making, and improved operational efficiency in TAM. The design and engineering data of BIM and the geographic context of GIS provide an opportunity for a comprehensive framework to manage these assets. Moreover, are discussed in detail the IoT-enabled systems, including sensor-based monitoring, in facilitating real-time data collection and predictive maintenance, especially their function as critical tools to serve SHM. The chapter aims to overall represent thoroughly and in a systemized way, the information necessary to study and understand the topic, and serve as the basis of any future proposals whatsoever.

Chapter III – This chapter outlines the conceptual framework of IAM, by demonstrating how operational needs should merge with financial goals and strategic objectives to keep assets operational and enhance their longevity. This framework unites organizational planning activities with engineering programs and financial administration protocols to handle environmental risks and changes in climate. There are explored the related standards and regulations, the asset's lifecycle and the challenges related to these.

Chapter IV – This chapter marks the start of the practical part of the thesis, with a smooth pass from the theoretical background of the role of sensor integration in TAM, describing their types, placement strategy to the proposal which comes as the result of gap identification performed based on the literature review. Additionally, in this section are explored the selected parameters to monitor for this thesis, being: temperature, humidity, vibration and hazardous gases. Such key parameters allow the monitoring of structural integrity, environmental factors, and traffic data and vital for stakeholders, providing essential insights into tunnel conditions for decision-making and risk management. The stakeholders serve as the party which is designated to be served by this proposal and their types and relationships to the proposal are discussed in details. How the sensor monitoring would boost their efficiency and in what practical way the data could be utilised is also explored, with a special focus on O&M team which are the selected main stakeholder to be served.

Chapter V – This chapter is dedicated to the technical part of the creation of the platform to be utilized for visualizing, analysing, and managing tunnel infrastructure data. The procedures for constructing the GIS are outlined, including the gathering and conditioning of data, as well as the representation of data in ArcGIS Pro and the incorporation of live sensor information. The interoperability between GIS and IoT is tested because the sensor data is simulated by a Python script and then run into the software and connected to the selected locations of the tunnel. After the GIS is officialised, the data are exported online and the Dashboard is built to visualize the data, as the ultimate goal for completing the proposal to the stakeholders' function.

Chapter VI & VII – The last 2 chapters, fit the traditional thesis structure by being dedicated to the discussion of the finalised product, the strengths and limitations that characterize the proposal. In retrospective, it is discussed on the weakness of the developed product and what could've been different, to enhance its functionality. Whereas the conclusion, serves as a wrap up of all the thesis, dedicated to the findings which can be an interesting contribution to the field and how they can serve as a start for future projects, including the perfect of such proposal with time and technological development and then its implementation possibilities, in terms of scale, asset type and overall feasibility analysis.

ABBREVIATIONS

IAM Infrastructure Asset Management

AM Asset Management

TAM Transport/Tunnel Asset Management

BIM Building Information Modeling

GIS Geographic Information System

IoT Internet of Things

PAS Publicly Available Specification

ISO International Standards Organisation

IAMS Infrastructure Asset Management Systems

AR6 Sixth Assessment Report

IPCC Intergovernmental Panel on Climate Change

EEA European Environment Agency

EU European Union

AASHTO American Association of State Highway and Transportation Officials

CTDOT Connecticut Department of Transportation

GASB Government Accounting Standards Board

OECD Organisation for Economic Co-operation and Development

UN United Nations

AMS Asset Management Systems

SHM Structural Health Monitoring

TSI Tunnel Service Index

NURBS Non-uniform rational B-spline

AI Artificial Intelligence

IDT Inspection Digital Twin

ML Machine Learning

IAMS Intelligent Asset Management Systems

DE Digital Engineering

AIR Asset Information Requirements

IIoT Industrial Internet of Things

GeoBIM Geospatial Information Systems (GIS) and Building Information Modeling (BIM)

LiDAR Light Detection and Ranging

MRT Mass Rapid Transit

DTS Distributed Temperature Sensing

DSS Distributed Strain Sensing

PPP Public Private Partnerships

MCDA Multi-Criteria Decision Analysis

CO Carbon Monoxide

NO Nitric Oxide

NO_2 Nitrogen Dioxide

O&M Operation and Maintenance

HVAC Heating, Ventilation, and Air Conditioning

ERT Emergency Response Team

WGS84 World Geodetic System 1984 Reference System

CSV Comma Separated Values

LIST OF FIGURES

LIST OF TABLES

1. Introduction

Infrastructure Asset Management (IAM) developed as an obvious need to find organized ways to maintain and improve public infrastructure. The term "asset management" emerged in the 60s, whereas "the physical assets" in the 70s. [1] By the mid-1990s, detailed guides like the National Asset Management Manual in Australia and the New Zealand Infrastructure Asset Management Manual were published, laying the groundwork for formal IAM practices. Such initiatives were integrated into the International Infrastructure Management Manual, published in 2000. [2] Thus, IAM is an integrated organizational activity for obtaining value from assets: planning, acquisition, operation, maintenance, and disposal of infrastructure. The major aims of IAM are maximizing the performance and life of the infrastructure assets with a reduction in costs and risks. IAM has gone through many developments in the past few years, mostly led by new technologies and the rising intricacy of infrastructure systems. Infrastructure asset management evolved because of an acute need for systematic ways of maintaining and optimizing public infrastructure. The notion of managing physical assets in a structured manner gained popularity in the 1980s-1990s.

The integration of several key technologies has significantly shaped the advancement of Infrastructure Asset Management (IAM). For example IAM is a multidisciplinary field today due to developing interchangeably with BIM, GIS, IoT, etc. These technological advancements facilitate better data collection and analysis. They also enable interpretation which then enhances the process of making decisions. The allocation of resources is also optimized. The use of these developments ensures infrastructure assets are managed more efficiently regarding sustainability aspects. [3] [4]

On a global scale, IAM is credited for creating standards and best practices such as the PAS 55 and ISO 55000 series. These standards ensure systematic sustainable management of assets. They bring about uniformity and effectiveness in various regions. [5] [6] This international standardization plays an important part in development and it also contributes to the refinement of IAM on an international level.

1.1. Context and background

IAM is the systematic management of infrastructures with the primary goals of promoting safety and efficiency throughout the infrastructure's life cycle. In Italy, the incident of the Morandi Bridge (Polcevera Viaduct) in 2018 has given a new focus towards the issues enveloping the administration of extensiveness infrastructure. Nevertheless, the bridge was recognized as having certain weaknesses In particular, corrosion was diagnosed in the 1980s, but the bridge remained in service without a comprehensive strengthening until its catastrophic collapse. This disaster brings into focus the inefficiency of conventional asset management strategies where lest we regularly inspect and carry out manual adjustments, sometimes without incorporating technological advances such as GIS or real time sensors monitoring.

Internationally, GIS applications in IAMS have been promising especially in transportation infrastructure systems. As mentioned, GIS tools help the stakeholders and all the related parties to better understand large data sets that are often difficult to analyze and understand, for instance distributions of assets, maintenance calendar, and condition reports.

The failure of the Morandi Bridge also raises questions about how existing monitoring solutions can be improved in order to be more user-centered while at the same time incorporating real-time data inputs. With a GIS-based dashboard in place, infrastructure managers are in a position to proactively undertake necessary measures to sustain or guarantee safe infrastructure. [7] [8]

1.2. Problem statement and objectives

Italy, Europe, US and commonly around the world, infrastructure has aged, especially the tunnels and bridges. Some monitoring systems exist but they are usually siloed, disconnected and are mostly designed to respond to problems rather than prevent them. Some of today’s systems for tunnel asset management, such as the current tunnels structures, for instance, do not have a coherent and comprehensive one-stop database for real-time data feed. This commonly results to a delay in maintenance interventions as well as escalates the risk of failure of infrastructure. Furthermore, since the data is scattered between different agencies and is in various forms, top management cannot obtain a consolidated picture of asset conditions to guide their decisions. Although there are some published tools that address infrastructure management, none could be found that would offer the necessary characteristics for a user to make effective decisions related to infrastructure. This thesis will seek to address these challenges by developing a GIS based system for tunnel monitoring though the information and system can be extended to other infrastructures or countries, by presenting the status of the assets to the first-line engaged professionals and then stakeholders in an understandable and engaging format. [9]

The main objective of this thesis is to develop a GIS-based dashboard for infrastructure assets, simply applied for a real tunnel located in Italy. This dashboard aims to represent:

1. User-friendly interface where the involved parties can understand every data they have as well as easily make decisions, even if they don't have a technical background in engineering.

2. Promote preventive preservation by detecting signals of decline at an early stage as cracks or corrosion as it was explained previous in the Morandi Bridge case.

3. Suggest developing a more generic model that allows for the addition of other infrastructure types, like bridges and highways.

4. Finally, embed the real-time data from the sensors for checking the conditions in the tunnel and other related structures.

To achieve these goals, the thesis will start off by analysing the historical development of asset management, assess current technologies implementation (like GIS, IoT, and sensor-based monitoring), and outline a feasible solution to improve asset management for broad use in different infrastructure asset types. The first part will be dedicated to representing a state-of-the-art analysis and the second one, the proposed solution.

1.3. Methodology overview

The work followed different paths for the literature review and for the solution development. Regarding the first part of the thesis, the research methodology developed into a step-by-step procedure. To start with, it was carried out a broad search through academic databases, whereby were collected a large number of papers and articles related to IAM. The first stage of this process was to familiarize with the vastly different and broad knowledge base within this field. However, it did not take long to realize that the information was too diversified and disorganized to draw even a semblance of coherent insight from it. In this regard, it was decided to categorize the sources systematically. The categories were as follows: foundational theories, methodologies, technological advancements, case studies, and industry best practices. This system considerably simplified the process of extracting and synthesizing the information. This process of categorization helped in managing such extensive literature more effectively and also provided with a more focused and in-depth analysis. It also allowed the identification of trends, gaps, and critical areas within IAM that were to be looked into deeply. The identification of these gaps majorly affected the concept of building an interoperable GIS-IoT solution for enhancing the stakeholder engagement and overall decision-making process of asset management. Each category belonging to the literature review will be presented in more detail in the subsequent sections, where will be described each category and discuss the insights drawn from this structured research. In this way, it's aimed to provide in-depth and coherent knowledge of IAM by contributing valuable insights to the field. The proposed solution was supported by many sources, in a process of going back and forth to the available knowledge and data. An elective course dedicated to GIS, learning ArcGIS software, following several tutorials and online forums, studying the existing visualization system and discussion with the people directly involved in the real-scale project development in Italy, to obtain data, insight and potential adjustment of ideas were the main supporting tools for the technical background of the solution. ArcGIS Pro and PyCharm were used in parallel to develop the GIS and Python script for the sensor data simulation. As an initial solution, the data were exported to Excel, and then to Notepad, in a constant process of editing in the ArcGIS Pro environment. Lastly, the GIS was exported to web and Dashboard service was used. The relationship of the whole is visually represented in the scheme below.

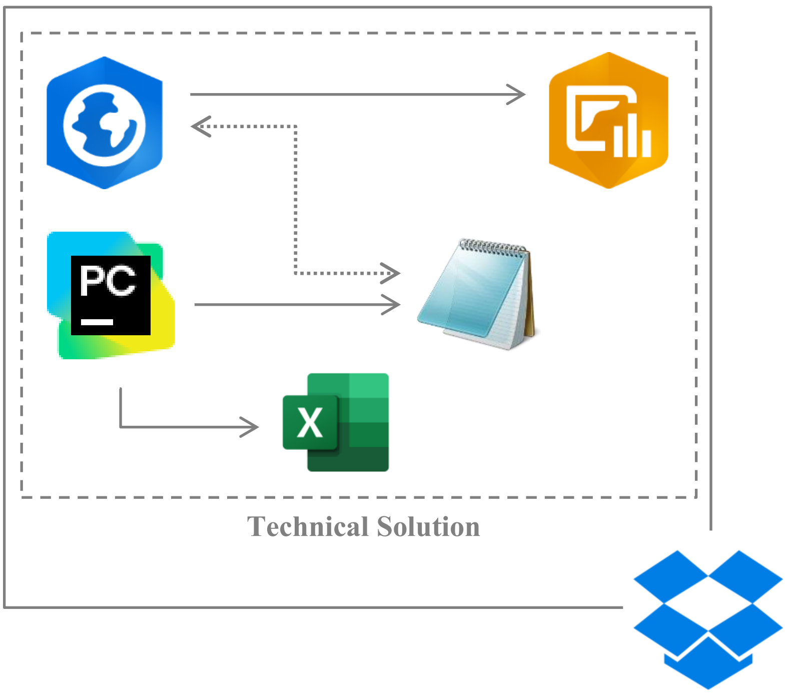


Figure 1. Interoperability Scheme

In the scheme, can be seen how all the project is stored in a shared data environment, Dropbox. The literature review has served as the source for the proposed solution. The logos of the involved software, platforms and else, have been strategically placed from left to right, to show their involvement in the project, chronologically.

2. Literature review – State-of-the-art

2.1. Infrastructure Asset Management

2.1.1. Definitions, importance and scope

IAM can be defined as a systematic and coordinated approach of comprehensively and effectively conducting the activities and practices that are required by an organization in order to efficiently and sustainably manage their infrastructure assets during their entire life cycles [10] This constitutes in the acquisition method, carrying out, maintenance, and disposal method, with the goal of improving performance at an optimal cost and minimized risks. It also contains financial, engineering and environmental factors which help organizations to make right decisions on their assets. It is important to note that IAM may be defined differently across various organizations and industries.

The concept of IAM is very important in tackling various problems encountered by governments and organisations globally especially in the urban centres where there is need to develop more sustainable and responsive structures. Moreover, IAM combines all these, including risk management and the use of technology to enhance the performance of the assets and their longevity. [10] [11]

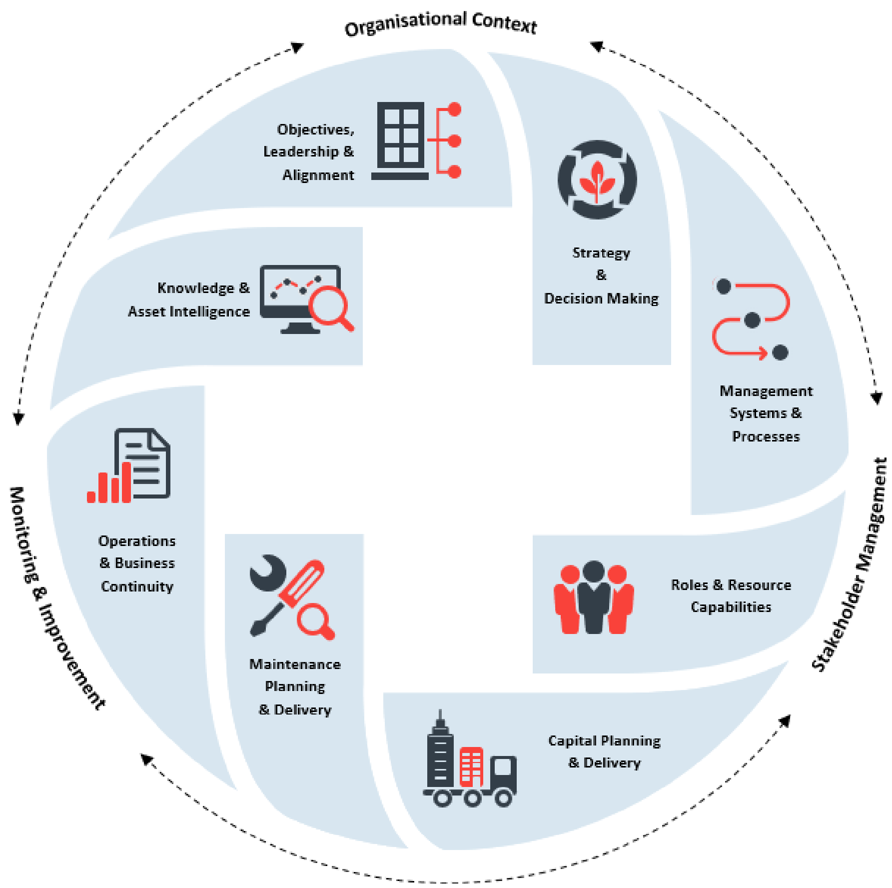


Figure 2. Asset Management **[86]**

IAM has become a critically important concept over the last few years for several reasons. Firstly, infrastructural decay across many developed countries raises frequent failures that threaten safety and cause huge losses. As estimated by the American Society of Civil Engineers the United States needs an extra infrastructure investment of around $2.59 trillion by 2029 [12] Secondly, there is now a better understanding of the effects of climate change on infrastructure systems to require the consideration of resilience in IAM strategies. Some climate change risks include flooding, rise in sea level, acts of extreme weather, rise in the cases of harsh and more frequent climate events that affect the performance and durability of many systems and services and that are likely to compromise the use and safety of any structure. [13] It can be argued that its importance is rooted in the role that it plays in the improvement of infrastructure reliability from disruptions like natural disasters and systemic breakdowns. In the AR6 Synthesis Report: Climate Change Review published by the IPCC in 2023, it is pointed out with high certainty that the future of infrastructure is under threat by climate change related hazards for which appropriate IAM strategies and solutions must be developed for transportation infrastructures [14]

IAM is more than just a maintenance endeavour – it also includes addressing all aspects of infrastructure systems. It contains the identification of the current status of the assets, future requirements, and decision-making on the basis of assessment data. As noted, IAM applies to all forms of infrastructure including transportation systems, utilities, and public facilities demonstrating the importance of the overarching framework that should allow for different kinds of assets and their condition. [13]

2.1.2. Relevance to transportation systems

Transportation networks have remained as vital aspects of every society's infrastructural development as they are involved in supplying essential services that enable economic development of a nation's economy, bringing people together in a society, and enabling security of individuals and property. Infrastructure Asset Management (IAM) has a critically essential function in maintaining that the functional physical transportation entities such as roads, bridges, tunnels and rail lineages, whether challenged or not by problems, perform optimally and are reliable. Effective management of transport assets guarantees availability and reliability and at the same time lowers overall cost while increasing the safety of users and operators. [15] Impacts arising from interruption of transport systems by breakdowns of transport assets or by acts of nature pose severe economic consequences. Transportation assets and facilities are very vulnerable to slow degradation and sometimes catastrophic loss because of natural calamities and other deterioration factors, wear, tear, and usage. Consequently, IAM strategies are crucial in managing risks bound to asset failure within the production process. For instance, system condition inspections conducted annually on bridges and tunnels can quickly detect areas of weakness that may cause devastating collapse by providing evidence for maintenance and/or replacement. Likewise, carrying out proper preventive measures that can enhance the life of the transport asset can go a long way towards reducing costly repairs and unscheduled downtimes. [11] One of the largest impacts of climate change is raised in the field of transportation where one of the most significant issues of IAM for transportation systems is considered. Storms cause damage to transport infrastructure including roads, bridges, and tunnels and frequent flooding disrupts transport systems. For example, according to the European Environment Agency (EEA), it is calculated that in the period 1980-2022, the losses in the economy due to the consequences of weather-related natural disasters in the European Union (EU) amounted to 650 billion euros, the consequences of which threaten critical infrastructure. [16] Higher sea levels and increased intensity and frequency of rainfall are also likely to contribute to a high possibility of flooding in coastal regions through which most global transport links and facilities are established. [14] To overcome these risks, IAM for transportation systems includes risk management and develop resilience plans. Thus, by completing a vulnerability assessment, asset managers decide which link in the transport network is most susceptible to the impacts of climate change. This information allows them to allocate resources for adaptation strategies like building flood defence structures, promoting better drainage systems, using advanced materials, real-time data gathering and analysing, etc. [11]

In conclusion, the relevance of IAM to transportation systems lies in its ability to ensure that transportation networks remain safe, functional, and resilient, even as they face increasing pressures from climate change, population growth, and aging infrastructure.

2.2. Transportation Asset Management (TAM)

Transportation Asset Management (TAM) is an essential framework for maintaining, operating, and enhancing the transportation infrastructure over its lifecycle. Highways, bridges, tunnels, transit systems and more create the transportation network which plays a fundamental role in the economic growth and life quality of a country. Effective TAM integrates engineering technology, economics, finance, and operating experience to achieve the best value of serviceability, safety, and utilization for transportation assets within the lowest life-cycle cost. [17] [18] The definition of TAM, according to the American Association of State Highway and Transportation Officials (AASHTO), is a strategic and systematic process that involves operating, maintaining, upgrading, and expanding transportation assets effectively throughout their life-cycle. This systematic process focuses on business and engineering practices for resource allocation and utilization based on high-quality data and well-defined objectives [19]

2.2.1. Definitions and principles

TAM can be regarded as the instrument used for control of physical assets' productivity, defining needed levels of service and optimal maintenance, repair, and replacement programs' costs. It entails selection of an extensive range of decision-making tools within the life-cycle cost analysis, performance measurement and risk management framework. [17] The use of condition-based metrics is one of the important principles of TAM wherein the current state of assets is evaluated in a manner that guides maintenance decisions. Through the constant assessment of the current status of transportation systems, TAM provides practical evidence of how better resource utilization and efficient use of available resources can be achieved while reducing the overall life-cycle cost and further prolonging the life of these systems. [18] For instance, Connecticut Department of Transportation (CTDOT) successfully applies TAM since the 70s, by developing performance measures that guide resource allocation, helping to maintain roads, bridges, and transit systems at desired performance levels. [19] TAM rose to popularity mainly due to the realization of the importance of managing infrastructure in today's organizations. Specifically in United States, the implementation of TAM has been precipitated by need to meet requirements of GASB 34 where all transportation agencies were forced to place value of infrastructure on their financial balance sheets. This regulation made agencies to focus on assessing performance of assets, integrate quantitative methods of financial management in infrastructure future planning. [20] In the early 2000s, TAM was adopted by countries such as Australia, UK, USA, and Kuwait [20] whereas today many countries from different economic status have come to realize the potential of TAM concepts for the expansion and modification to fit and improve the existing and future local and international demand for transportation.

2.2.2. Key challenges

Despite the benefits of TAM, several key challenges persist in its implementation. One substantial problem is the integration of data from multiple sources and different types of assets. [19] From the literature review one of the biggest challenges that has been identified is the ability to link different asset management systems across the various modes of transport. It is common practice that different agencies are in charge of roads, bridges and tunnels and trains and these can result in many problems in their administration and data collection and organization. [20]

Another issue is the conflict at the level of goals with TAM between political considerations and available budgets. Since transportation agencies work within a political environment, the procurement of sufficient resources and the synchronization of TAM goals with the fluctuating political landscape can prove perplexing. For instance, short-term political goals like capacity expansion might negate the maintenance strategies of TAM. [19] There is always a tension that drives agencies to opt for the repair solution instead of a preventive measure and these have been found to cost more and reduce the lifespan of the assets.

Furthermore, the consequences of climate change increase the challenges to this balance. More frequent extreme weather events such as floods and heatwaves also cause deterioration of transportation infrastructures leading to the need for resilience enhancement. [21] [13]

Lastly, opportunities are provided by modern technologies, including sensor-based monitoring systems and predictive maintenance tools, which appear to rise to these challenges. These technologies aid in real time collection of data and analysis hence the asset managers can institute measures to check on any failure that may arise. However, the deployment of these technologies across vast transport networks involves considerable capital outlay; moreover, there are issues that relate to the assimilation of data from various systems into the overarching TAM framework. [17]

2.3. Tunnel Asset Management (TAM)

Tunnel Asset Management (TAM) can be identified as a subcategory of Infrastructure and Transportation Asset Management but has more complications mainly because tunnels are unique structures with specific environments and with considerable consequences in the event of their failure. This is because tunnels provide backbone to transportation systems, especially where essential paths of roads and rail tracks, as well as utilities are anticipated. TAM has a relatively high importance nowadays because of the tunnel infrastructure aging and growing effects of climate change which influences natural risks like floods, landslides or earthquakes. The key activities of effective TAM include assessing condition, preserving, managing risk and implementing technology to enhance the safety and performance as well as the durability of tunnels.

2.3.1. Specificities

Tunnels are different from other infrastructure categories such as bridges or highways when included in IAM systems based on the following challenges inherent to them. Tunnels are built to function in conditions that are highly stressful and include forces like the earth pressure, hydrostatic pressure, and dynamic loads from the vehicles. Hence, there's a need for more frequent inspections and that maintenance regimes are far more rigorous.

Among the key issues specific to TAM is the problem of soil-structure interaction. With the ever-increasing urbanization and the need to use the space more efficiently therefore the tendency to construction more tunnels, these are built on heterogeneous soil matrix meaning their structural behaviour is influenced by surrounding geological conditions. These dynamics mean that assessing tunnel response to loading condition is difficult and, consequently, calls for complex simulation tools during the design of tunnels as well as the necessary geological explorations. [22]

Another specific challenge is water management. The ingress of water, due to high groundwater levels or inadequate drainage systems, can accelerate the degradation of tunnel linings. In the long run, it results in failure, expansion, cracks, and could lead to complete building collapse if not controlled. To counter this, there is a need to ensure proper construction and installation of drainage systems and waterproof membranes as well as timely detection of any moistures seeping into tunnel structures. [23]

Finally, tunnel safety measures especially in those that are used by vehicular and rail transport are important because the tunnel shapes a closed enclosure and there are various dangers which for instance may include fire outbreak and derailing. Stringent safety requirements focus on various aspects like fire prevention, ventilation systems, and emergency evacuation routes. The necessity of real time monitoring is real for fire safety. It can be here underlined the catastrophic examples such as Kaprun disaster that happened in Austria in 2000, and caused 155 victims and Daegu subway fire, in South Korea, in early 2003 that caused 192 victims. Both cases weren't reported properly due to loss of contact with control centre and officials. Had there been implemented, hypothetically, fully-functioning real-time monitoring system, the response time would've been reduced. Most certainly, in a timespan of more than 20 years, considerate advancement has been reached and such cases remain isolated, but ensuring they are absolutely not-present and their effects minimize, a giant investment belonging to the future, is required. Emergency systems should synchronise perfectly to allow evacuation during incidents and the structures put in place should comprise features like standard exits and good ventilation for smoke control. [24]

2.3.2. Tunnel maintenance and monitoring strategies

Tunnel maintenance practices include those that are proactive in preventing future problems, as well as those that are called for in response to current tunnel issues. Just like its name suggests, reactive maintenance is the unearthing and correcting of "wear and tear" issues. This approach is widely used in the traditional way all assets are managed. On the other hand proactive maintenance aims at addressing issues likely to affect the tunnel performance. This can be illustrated with the following examples: include additional elements to reinforce the tunnel structure, an upgrade of the ventilation to accommodate increased traffic flows, etc. [20] [25]

2.3.3. Current development

Current trends in the management of tunnel assets have been triggered by technological developments and enhanced consciousness of the need for building new tunnel infrastructure that would adhere to global standards and principles of efficiency and sustainability. The convergence that has been evidenced in the projects is the use of technology tools such as Building Information Modeling (BIM) and Geographic Information Systems (GIS); which facilitates efficient management of the tunnel infrastructure since these provide details in form of digital images and spatial data respectively. For instance, BIM can enable the collaborative organisation of tunnel lifecycle information ranging from design and construction to asset management in a single information environment. [26] [27] [28]

Another significant advancement is the application of the IoT technologies, especially in the monitoring systems facilitated by sensors. Integration of different IoT sensors helps monitor the status of the tunnels and the real-time data collected can effectively be used by the asset managers to take appropriate action and reduce the occurrence of hazardous conditions or any form of degradation. Great emphasis is also placed on the use of artificial intelligence (AI) and machine learning algorithms to process this data and enable the use of preventive, maintenance-related strategies for prolonging the service life of the tunnel and the minimization of potential failure risks. [29]

Finally, since climate change is likely to increase the occurrence and intensity of natural disasters, there is an increasing focus on the protection of tunnel systems. This entails architectural and engineering approaches in constructing the tunnels to address the disasters, constraints incorporation of renewable energy systems in managing the tunnels, and utilization of environmentally friendly construction material in the tunnel projects. Technological innovation and increasing concerns for sustainable management of tunnel assets will define the future of tunnels as infrastructural systems, guaranteeing availability, safety, and reliability in response to emerging risks and demands. [14] [13]

2.4. Risk management and resilience in transportation infrastructures

Transportation infrastructure is subject to numerous risks that affect its long-term functionality and reliability. In this case, resilience is the capacity of the system to continue running and quickly recover in case of disruptions. The term risk management on the infrastructure means that one has to work out strategies of guarding against risks and avoiding events which will damage the assets, Similarly to the previous key concept, this idea implies that risk management is not a mere reaction to threats and threats, but a planned and proactive process of safeguarding assets and guaranteeing sustainability. In this chapter, it will be presented the traditional explanation of the infrastructure deterioration, the increasing prevalence of climate and natural disasters, the frameworks for resilience, and the key approaches in handling these risks.

2.4.1. Traditional deterioration

Conventional degradation in transportation infrastructure stems from their use, exposure to harsh conditions, deterioration of the construction materials, etc. By and large, pavements develop cracks and roads deteriorate through use, corrosion of bridge structures, wear and tear of road surfaces through massive traffic load, chemical attacks, and fluctuating weather conditions. [30]

As mentioned earlier, there is evidence that the process of degradation is indeed affected by a number of parameters that include material characteristics, traffic and maintenance regimes.

For example, the service life of asphalt pavements greatly depends on workmanship and traffic level – with higher traffic, the pavement degrades faster. In the same way, external factors such as climatic conditions and drainage age and system significantly diffuse or advance the deterioration process. Maintenance is critical to maintain infrastructure's useful life by repairing features resulting from material degradation and external loads. [31]

The overall costs of preventive maintenance will generally always be substantially less than its immediate repair counterparts as it helps with early identification of minor faults that are outstanding which may be necessitating costly expensive repair procedures when they result to severe problems. Nonetheless, resource constraints often make it impossible to adhere to routine maintenance schedules, and this accelerates the degradation process and increases repair costs. Lack of regular schedule results in complications can lead to failure, consequently increasing the chances of costly repairs. Even though in the short-term it requires more resources a successful implementation of the preventive maintenance has been proved to offer more benefits in terms of saving costs over the life cycle of the assets through reducing regular, costly and urgent repairs. [32] [33]

Figure 3. Different tunnel-related real-life accidents **[36] [87] [88] [89]**

(1) flood (2) fire (3) earthquake (4) debris falling

2.4.2. Climate change and natural disasters

Climate change threatens transport infrastructure by exposing it to issues that alter the manner in which structures previously performed or were constructed. New challenges include increased average global temperatures, increasing sea level, and more intense and frequent hurricanes, floods, and wildfires. These climatically driven alterations further amplify the risks associated with infrastructure in areas that are prone to flooding for instance along the coastal regions and areas with low land elevations. For instance, change in climate patterns may result in floods, affecting tarring of roads, excavation of bridges and construction of tunnels, extreme temperatures and unpredictable weather conditions may accelerate the deterioration of infrastructure. Research also reveals the effect of climate on increasing the occurrences of natural disasters that cause loss of infrastructure and affect services. [34] [35] The first image, which is part of the collage in Figure 2, illustrates an event occurring on 30 December 2023 in London, where a tunnel under the River Thames, flooded due to a burst pipe triggered by the heavy rain, and resulted in 41 cancelled trains. [36]

Coastal areas are highly vulnerable to risks such as erosion and floods, posing significant threats to the stability of transportation infrastructure, including roads, bridges, and tunnels. These vulnerabilities are exacerbated by climate change, with rising sea levels, higher temperatures, and more frequent hurricanes, floods, and wildfires. As these conditions persist, accelerated erosion and increased rainfall contribute to corrosion and undermine substructures, further compromising structural stability. Addressing these challenges requires substantial capital investments in adaptation measures, such as constructing high-level roads, enhancing drainage systems, and utilizing climate-proof building materials to safeguard infrastructure in coastal zones. [37] [38] [39]

More so, as climate related risks rise, it is evident that measures to improve the resilience is now a must. In addition to enhancing the resilience of infrastructure, these actions decrease the life cycle costs of infrastructure mainly because of repair and re-building after disasters. According to the World Bank (2021), it is crucial to mainstream climate risks as it also shows that adapted investments can lead to substantial savings through avoiding future disaster costs. With the overall cost presumed to be more than that of the conventional infrastructure, climate-resilient designs are receiving attention from the policymakers and engineers as they understand that any additional cost incurred in the initial phase can actually prove costly in the longer run. The OECD, World Bank and UN Environment forecast that the world will require USD 6.9 trillion of annual investment in infrastructure by 2030 in order for infrastructure investments to be aligned with the Sustainable Development Goals and Paris Agreement. [40]

2.4.3. Theoretical models and frameworks of resilience

The concept of resilience in transportation infrastructure has evolved significantly. It is now defined as the ability of a system not only to resist failure and predict the occurrence of disturbances but also to continue and return to normal operation when a disturbance occurs. Interestingly, this expanded view of resilience now begins to encompass more than just a restoration of things to their pre-disruptive state. It includes adapting to new conditions and restoring functionality through improved processes. This perspective reinforces the idea that resilience is essential for maintaining asset functionality, especially under stress or in post-disaster conditions [41] [42]

Anticipation, absorption, adaptation and recovery are four distinct stages of resilience cycle theory that are instrumental to strengthen infrastructure systems under pressure. The idea behind this approach is to make it possible for infrastructure to be ready to cope with disruptions, recover, and be ready for the next threat. The cycle begins with anticipation, preparing systems to forecast and mitigate potential threats. While in the absorption phase, organisations look at how the system can handle and absorb the initial effects of disturbances. Recovery is the process of bringing the systems back to their full functions, while adaptation involves learning from the disruptions most often to enhance the capacity of the infrastructure needed to handle the disruptions. [43] Studies carried out on critical infrastructure resilience also substantiate this framework by indicating that for systems, it is not enough to restore their functionality after being disrupted but also build up their capability to withstand future shocks. [44]

Resilience-based design integrates key features such as robustness, redundancy, and flexibility into infrastructure to ensure its functionality in both routine and crisis scenarios. This approach is in-line with resilience theory since it develops the ability of the systems to respond to worst-case scenarios, and recover rapidly from disruptions regardless of their predictability. Resilience-based designs incorporate mechanisms like alternative pathways, robust materials, and adaptive technologies to withstand and recover from challenges. Integrating resilience-based design elements, such as the ability to withstand disturbances and recover quickly, helps reduce infrastructure vulnerability to both natural and human-induced disruptions. These designs make it possible for infrastructure to be functional regardless of the situations that will be experienced. To quantify resilience, metrics such as performance evaluations, resilience curves, and the resilience index have been identified, helping engineers assess infrastructure suitability and determine necessary improvements for long-term stability in high-stress regions. These metrics assist the engineers in determining how suitable this infrastructure is and what steps should be taken to keep or improve it to provide better long term stability in stressed regions with quicker recovery periods. [45]

2.4.4. Risk management strategies

Effective risk management in transportation infrastructure relies on risk assessments, continuous monitoring, and targeted mitigation measures. Risk assessments are crucial for identifying potential threats and evaluating their impact on infrastructure systems. Such assessments assist the engineers in determining which risks should be handled first, depending on features like the risk impact and chance of occurrence. These assessments are then followed by preventive measures, monitoring systems and preventive controls that are in place or corrective actions. The objective is to minimize the risks to the maximum extent possible while increasing the ability of infrastructure to respond to such contingencies. For example, risk management strategies include the establishment of systems that constantly assess infrastructure conditions and the establishment of well-coordinated contingency plans in case of failure or disruption. [46]

Technologies that include the use of IoT sensors and remote monitoring systems are fast becoming key components in improving infrastructure management. They offer real-time data – a factor that is most useful in maintaining equipment to prevent them from failing. IoT sensors monitor infrastructure conditions, enabling early problem detection, minimizing unplanned downtime, and reducing maintenance costs. Also, they facilitate timely action on new challenges; consequently, infrastructure systems continue to perform optimally under normal or contingent circumstances. [47] The use of predictive analysis has become an important tool in infrastructure management especially for aspects such as asset reliability and maintenance costs and unscheduled downtimes. These technologies, using IoT sensors, machine learning, and many other forms of data processing, can indicate when and where structures may fail, allowing for maintenance instead of repair. This shift enables organizations to decrease the time that a specific piece of equipment is out of order by up to 50%, and sometimes potentially lower total maintenance costs by as much as 18% of the total, depending on the circumstances and the application. These systems not only predict failures but also determine optimal maintenance timing, reducing costs by allowing scheduled upkeep during low-demand periods rather than emergency repairs Predictive analytics is based on historical and real-time data and assists in managing the functionality of infrastructure assets, thus improving operational flows and reducing interruptions. [48]

2.5. Pairing with other technological developments

Modern IAM incorporates technologies such as BIM, GIS, Digital Twins, and IoT to enhance asset management, monitoring, and strategic maintenance. These technologies offer real-time information at different stages of the asset life cycle thus improving decision-making process, cost optimization and reliability. Integrating BIM, GIS and digital twin has been of most benefit in infrastructures that are complicated such as the tunnels and the large transport systems.

BIM and GIS are closely interconnected, enhancing real-time asset management and providing powerful tools for visualizing and analysing infrastructure. By adopting these technologies, organizations can create digital replicas of infrastructure, enabling real-time monitoring and continuous enhancement throughout the asset lifecycle.

Integrating Digital Twins with asset management systems has the added advantages of enhanced predictive maintenance and lifecycle management especially so when dealing with delicate structures such as railway systems. Through digital twinning, the physical infrastructure is duplicated in a digital form so that asset managers can monitor the performance parameters and emerging deterioration patterns [49]

2.5.1. Building Information Modelling (BIM)

The use of Building Information Modeling (BIM) has revolutionized asset management by facilitating the creation of a digital image of asset infrastructure. In IAM, BIM is critical especially in the delivery of an asset management life cycle from construction to the disposal phase. According to Blumenfeld et al. [26] BIM enhances visualization and management of assets through integration of data from Asset Management Systems (AMS) with BIM model. This integration enables tracking of infrastructure conditions in real time and hence the ability to make proper decisions in regard to the assets' maintenance. Besides, incorporation of BIM with sensor information facilitates early intervention hence preventing disruption of service and occasional failure of structures like bridges, tunnels, and others.

BIM has become an irreplaceable tool in IAM because of its ability to store data in detail and simultaneously, providing real-time information throughout the lifecycle of existing physical infrastructures. The application of BIM with the Asset Management Systems enhances infrastructure management and planning, and execution leading to smooth functioning and better decision making.

Additionally, according to Blumenfeld et al. (2022), BIM streamlines asset management by connecting semantic information (such as maintenance records and inspection reports) with the geometrical attributes of infrastructure, creating a centralized repository of information. As a result, it enables the asset managers to always be watchful of the infrastructure state, carry out preventive maintenance, and efficiently utilize available resources. Furthermore, BIM allows for the use of digital twins which are the digital replicas of physical assets and are useful tools for evaluating and forecasting asset status and behaviour into the future.

Blumenfeld et al. (2022) highlight data transfer challenges across different project phases, including design, construction, operation, and deconstruction. In large scale facilities involving complicated infrastructure like tunneling, data is often scattered in different systems causing data loss or gaps within interfacilitating and exchanging information among the involved parties. BIM eliminates this problem by encompassing all such information in a central system that exhibits the current state of the infrastructure making them easily accessible to the various stakeholders.

In tunnel asset management, BIM is a powerful tool that helps to visualize the underlying infrastructure. Whereas bridges or roads can easily be accessed for inspection, tunnels are often located underground or within mountains which can make a physical inspection challenging. The condition of stress, temperature, humidity, or displacement of a tunnel, for instance, can be monitored through sensor data from Structural Health Monitoring (SHM) systems, in conjunction with BIM models, without physical assessment of the tunnel. The data should be fed into the digital model in order to enable managers to virtually tour the facilities, experiment with a variety of operational conditions, and schedule maintenance work ahead of time.

Specifically, when applied to Tunnel Asset Management (TAM), BIM serves well as an effective environment for the integration of SHM systems. Currently, the sensor data of structures is being fed directly into the BIM models so that the managers of the asset get to see the real-time performance of the tunnels along with a picture of the structural health of tunnels coupled with several factors. This approach has been used effectively in several operating case studies for instance the Canalone Bridge Case Study project in which BIM was used in tracking data of SHM and/or maintenance requirements. This enables infrastructure conditions to be checked frequently so that managers can identify problems such as material deterioration, water leakage, or structural subsidence at early stages. Such a preventive measure helps to avoid costly repairs when important infrastructure wears out and also helps in ensuring that the infrastructure has a longer life span. [50]

2.5.1.1. Digital Twin (DT)

Digital twins have become truly transformative when it comes to Tunnel Asset Management (TAM), especially when it comes to conditions, degradation prediction, and maintenance management. A digital twin can be described as a virtual model of an infrastructure asset that is updated consistently with data obtained from the actual asset to help managers monitor performance issues and predict future requirements. [27] emphasizes the value of tunnel degradation prediction models that incorporate empirical data to predict performance loss over time. Such models enable asset managers to forecast when maintenance or rehabilitation efforts are needed, thus preventing service interruptions, such as applied for the Shanghai Subway. The paper points out the benefits of these models that use historical and real-time data to assess the rate of degradation. For instance, the Tunnel Service Index (TSI) is a measure used to evaluate the performance of a tunnel based on factors such as the average settlement, crack propagation and spalling area. These indicators are used to input a deterministic or probabilistic model to determine the time for maintenance or rehabilitation of a tunnel. When combined with a digital twin, this model enables asset managers to see the current state of the tunnel at any given time, monitor how degradation is advancing over time, and determine the most auspicious moment for maintenance intervention to prevent expensive breakdowns.

Apart from the assessment of degradation, the digital twin also enhances the accuracy of the inspection process. Conventionally, there are a number of control measures that are adopted in tunnel inspection, which can be time consuming and carry along with them the probabilities of human error. By integrating digital twin with SHM systems, the managers of assets will be able to automate the task of inspection, specifying the regions of interests from the sensor data acquired. For instance, in the work by Machado, Bellini & Massao [27], one can find an explanation of how NURBS technology can be used to generate intricate models of geometries of tunnels so that their inspections have increased accuracy and the probability of an omission is minimized. It improves the effectiveness of the degradation analysis that enables the asset managers to plan repairs and extension of the asset with greater precision.

Within the railway industry, digital twins have been adopted with success in the optimization and control of railway systems. Stalder et al [49] discuss the application of digital twins in clash detection and scheduling of the maintenance. In rail networks, which are usually complex systems with operations of multiple maintenance activities at the same time, it is possible to experience clashes between work teams that results in costs such as time costs, financial costs, and even possibly compromise safety. Digital twins reduce the need of human intervention when detecting clashes because the digital model simulates the entire rail network to help in determining if there are any schedules clashes that have not been scheduled for.

Moreover, with digital twin technology, it is possible to envision a representation of asset performance at various layers of information. In the railway context, this may encompass the examination of real-time information about the state of the track, the speed of trains, weather conditions or other potential dangers in the environment. When these streams are fed to the digital twin, asset managers are in a position to virtually experiment on different operational situations, like harsh weather conditions and equipment breakdown, and gauge the readiness of the rail network. For instance, in rail networks where track conditions must be monitored continuously, digital twins can provide real-time feedback on track alignment, wear, and temperature fluctuations. SHM systems coupled with digital twins can enable rail operators to identify and monitor small changes in the rail condition that could lead to derailments or major failure. This kind of maintenance approach has the added advantage of a cut down life cycle cost and minimised maintenance time; the maintenance is done on the basis of the actual need and not an anticipated period of interval. As a tunnel application may be mentioned the Gotthard Base Tunnel in Switzerland, the world’s longest railway, which is operated with the help of augmented reality to monitor the tunnel’s condition in real-time. Various sensors placed at different locations of the tunnel return data to the digital twin where information on how the tunnel reacts to stressors such as ground shifts or increased traffic loads is mimicked. This allows asset managers to prepare for potential failures and strengthen the problematic areas before they become an issue. [51]

It is evident that the overall usage of BIM and its operational digital twin for infrastructure management has its pros and cons; however, its downside is a few challenges that have not entirely embraced the implementation of the systems as a whole yet. According to Blumenfeld et al. [26] one of the primary challenges is the need for standardization across different infrastructure sectors. To date, there are no industry standards for interchanging data between BIM models, digital twins, and AMS platforms, which may lead to inefficiencies in data exchange. The authors recommend that open data standards are critical to the success and adoption of digital twin technologies.

Furthermore, there are some socio technical implications in connection with the training of the personnel to manage these sophisticated systems. Following Stalder et al. [49], the application of digital twins for railway and tunnel management also relies on changes in the disciplines' technical competencies and on the organisations' culture. Asset managers must learn not only how to analyse data gathered through digital twins but also how to align this data into the strategic management process.

Moving forward, the use of artificial intelligence (AI) in the further development of digital twins is anticipated. A consequence of embedding AI algorithms into digital twin systems is that fixed intensive data analysis can be done automatically, making the predictions of the infrastructure performance much quicker and accurate. Another way that AI can be used is in maintenance management that involves an assessment of past occurrences and a prediction of the likely failure areas at any given time.

2.5.2. Geographic Information System (GIS)

Geographical Information Systems (GIS) are vital in IAM, as they provide spatial data that allows managers to visualize and assess infrastructure within its environmental context. Regarding infrastructure, GIS allows assets managers to visualize whereabouts such structures are located, the shape that they undertake and how they spatially relate to other features within a contextual scale such as a county or region, whether or not that area is prone to natural phenomenon such as earthquakes, floods or landslides. GIS has been depicted to be utilized in partnership with BIM in generating digital systems of infrastructure systems, as illustrated by the Federal Highway BIM Initiative of Germany where BIM together with GIS were applied in the management of road and bridge infrastructure [28]. GIS data can be incorporated into BIM models, thereby helping the asset managers to make more informed decisions on the geo-referenced risks of infrastructural assets in need of maintenance. These spatial data are then associated with BIM models that give a complete picture of the internal environment of the tunnel and the possible environmental hazards. The Inspection Digital Twin (IDT) methodology, as described by [27] demonstrates the power of utilizing digital models for tunnel inspection and maintenance. When integrated with spatial data, 3D models of tunnels help the asset managers to mitigate possible risks before developing into incidents.

2.5.2.1. ArcGIS Pro – Dashboards

ArcGIS Pro is a software that can be used in asset management that focuses on IAM and TAM since it supports asset data visualization, management, and analysis. Here's how ArcGIS Pro can be used in these contexts:

1. Real time monitoring and predictive maintenance

ArcGIS Pro provides functions to connect IoT sensors and real-time data feed into the GIS operations. This is beneficial especially in infrastructure and transportation assets where the sensors that may be installed in tunnels, bridges or roads can aid in monitoring parameters relating to its performance such as temperature, vibration or even stress level. It then processes it with the objective of assessing areas of weakness, anticipated maintenance needs, and the general aim of preventing expensive failures by encouraging predictive maintenance. [52] [53]

2. Data Centralization and Visualization

ArcGIS is a single interface for handling various data like maps, records of assets and even real time performances to name but a few. This is particularly important to project such as the management of tunnels which are regarded as large infrastructure projects and which normally have information dispersed in various systems. ArcGIS Dashboards solutions built allow asset managers to navigate between multiple assets—enabling them to get a better understanding of the current state of infrastructure, assess maintenance/replacement schedules, and direct personnel & resources. [53] [54]

3. Lifecycle Optimization

ArcGIS supports the entire lifecycle of an asset, from construction to the management and decommissioning. It links up with asset management systems to offer current status of the condition and performance of the assets. They do this by identifying geographic patterns and trends through geospatial analysis which facilitates effective asset management throughout the asset lifecycle especially in transport infrastructure where high levels of interconnectivity exist. [54] [55]

4. Risk Management and Decision Support

This way, ArcGIS enables asset managers to evaluate risks since the geospatial data (for instance, terrain, weather patterns, or close locations to threats and vulnerabilities) can be overlaid with infrastructure performance data. This integration provides the foundation for decision making on the allocation of resources and the management of risks to transportation systems. [53] [55]

5. Stakeholder engagement

This application is highly facilitated by Dashboards service of ArcGIS, which enable the presentation and communication of information to other users and stakeholders. They produce customized formats of reports and graphical interfaces that can be relayed to multiple departments in an organization and facilitates synchronizing of maintenance, business, and risk management strategies. Thus, through simplicity and providing ample information, dashboards support performance and enhance interactions with other people, including engineers, planners, and decision-makers. [53]

However, as will be further discussed in the subsequent sections, ArcGIS for asset management is much more than the simple visualization of assets. Although this description showcases the ability to monitor assets and data in real-time, centralize data and perform preventive maintenance, the ArcGIS strengths lie in constructing complex systems that enhance the assets and decision-making cycles of their lifecycle. In the subsequent sections, we will further discuss how the features of ArcGIS Dashboards provide superior decision support with spatial analysis and how integration of IoT and sensor with monitoring approach contributes to preventive maintenance in civil structures, especially tunnel and transportation systems. Furthermore, case studies will be adopted to highlight how ArcGIS can revolutionize asset management practices and its benefits to improve resource efficiency, resilience, stakeholder engagement and more.

2.5.3. Internet of Things (IoT)

2.5.3.1. Sensor-based monitoring and real-time data in tunnel management

The Internet of Things (IoT) has revolutionized Infrastructure Asset Management (IAM), transforming how infrastructure assets are monitored, maintained, and managed. IoT can be defined as the interrelated devices, sensors and systems to transmit and share data real time and assist the asset managers on asset performance and maintenance schedule. In the broad IAM context, IoT plays a significant role in enabling real-time and/or automatic inspection of essential factors of infrastructure constituents in a manner that would otherwise require considerable investigations of the physical state of the asset.

Both the conventional AM and the emerging TAM, as well as the use of IoT in those two sectors, offer numerous advantages to improve sustainability and operation of tunnels and other contexts. As stated in [56] the current UK rail industry has been proved to have had more than a hundred percentage increment in the usages of service within the framework of the last twenty-one years; therefore, it requires competitive methods in the management of assets. A qualitative analysis identified nine critical problem areas in rail asset maintenance, emphasizing the need for real-time condition monitoring, predictive maintenance, and remote inspection capabilities. Rail operators can effectively improve the management of asset information on their fleets by integrating a detailed IoT system that includes a cyber-duplicate of the entire physical assets and collecting and leveraging big data to achieve better usage of assets. For example, IoT technologies can help monitor tunnel environments and make constant adjustments to avert dangers correlated to structural breakdowns. AI as a tool in the [57] paper also explains how AI and, in particular, machine learning techniques or deep learning might improve the estimates of the financial market and asset management planning. Studies have shown that through the use of these sophisticated analytical tools, forecast of key economic ratios is enhanced and therefore applying AI in AM enhances decision-making regarding resource allocation. In the area of financial forecasting, the research has revealed that Machine Learning (ML) can be used to forecast the stock returns, as well as the volatility, highlighting the ways in which AI can be used to streamline the asset management procedures.

One excellent example of IoT applicability is noticed in the conception of the integrated cloud based platform for asset management in the elevated metro rail projects. Real-time tracking of equipment and machineries is possible by this platform; thus reducing paperwork on record keeping by 30% [58] Moreover, the cycle time for casting precast segments was reduced by 17 percent, and the transportation times increased by 50 percent, which can be considered as a significant improvement of productivity. [58] Such advancements are crucial to the IAM and TAM processes as real-time data helps to achieve higher levels of collaboration between industry players and stakeholders.

In the railway sector, it is possible to note the evolution from the traditional strategies, which are based on the reactive and the preventive asset management methodologies, to the more complex prescriptive methodologies, as presented by DAYDREAMS project. The project focuses on the implementation of prescriptive analytics and artificial intelligence to improve operational performance and deal with intricate asset management issues [59]. Thus, the presented work highlights the need to have common catalogues for tracking digital assets related to the Intelligent Asset Management Systems (IAMS) prototypes in intelligent maintenance contexts. In this integration, preventive and ongoing assessments of the system are achieved in real time, enhancing safety while at the same time cutting down on costs incurred.

The efficient tracking of infrastructure assets is becoming even more paramount, taking into consideration the much older infrastructure, which according to [60] in 2015, has an estimated value of about €48 trillion within the European Union alone. This is particularly so, where distribution of assets prove to be complex and challenging to mainstream theorisation, such as in tunneling; there is therefore the need for innovative approaches towards the application of AM. Although organizations still adhere to the principles that were provided by the PAS55 and ISO 55000 standards, they often fail to employ adequate predictive maintenance techniques; essentially, this leads to the increase of costs. Technologies like big data and IoT enable consequential models which are capable to equally schedule the maintenance of the assets through the actual or real condition of the assets. For instance, the use of these technologies recorded an 87% decrease in scheduling time and a 47% improvement on construction crew productivity [60].

A systematic literature review by [61] points to the growing trend of DE tools in IAM, especially in the context of TAM. The review showed that there was a general shift towards the adoption of DE technologies like BIM and GIS. One of the identified outcomes was the development of the Digital Technology Integration Matrix that helps decision-makers sort DE tools by the Asset Information Requirements (AIRs) they capture, enabling efficient data gathering for tunnel asset management. Interoperability among the DE tools is given priority to enable smooth data sharing, which is an essential aspect of the complexities inherent in tunnel construction.

IoT and IIoT have been highlighted by [29] as one of the powerful tools that would greatly revolutionalise asset management. Reducing the downtime and maintenance costs, it is the outcome of utilizing predictive analytics on real-time data – a key to success in TAM as the uninterrupted functioning of infrastructures is critical. However, since IoT is a combination of interconnected systems, there are risks that come with security measures and the need to formulate effective risk assessment to mitigate the probability of the cyber threats [29].

In addition, the system proposed by [62] called T-Vision shows various improvements in the tunnel inspection application with its 360° infrastructure inspection radar. This system is non-destructive subsurface inspection which helps to detect the subsurface irregularities and useful for maintenance information. The inherent wide range coverage and detection functionality enhance safety and operational reliability on railway tunnels besides enabling prompt interferences of preventive maintenance [62].

Finally, the application of IoT and other technologies in the management of assets have enormous potential to offer robust solutions for improving operation and safety in tunnel asset management. Through the utilization of real-time data analysis, effective monitoring of equipment and structures health, and employing novel technologies in detecting defects, organizations can enhance their asset management and make infrastructure solutions long-lasting and sustainable.

2.5.4. Integration

The integration of the previously examined technologies varies in quality and quantity. To start with the integration of Building Information Modeling (BIM) and Geographical Information Systems (GIS), which is gaining significant traction within Infrastructure Asset Management (IAM). Such integration offers great enhancements in terms of information flow, process enhancement and decision-making. According to Garramone et al. [63] the blending of these technologies — termed "GeoBIM" — presents a powerful solution that combines the structural and engineering data of BIM with the geographic context provided by GIS. In conventional infrastructure management systems, each component is managed independently and does not allow for an understanding of how an asset in question interacts with the surrounding environment, whether it be roads, bridges, tunnels, etc. On this front, GIS offsets this weakness by providing spatial data to support depiction and tracking of an asset's context with regards to its larger coverage geography thus is most advantageous in infrastructural fixated systems. On the other hand, BIM provides a detailed representation of design and engineering aspects which are crucial in delivering information about structures and operational capacity of assets. The incorporation of Building Information Modelling (BIM) together with Geographic Information Systems (GIS) currently used for IAM is truly a revolutionary approach as it helps make urban infrastructure more efficient, sustainable, and resilient. It all comes down to the convergence of geospatial data from GIS which gives the context in the geography and visualization capabilities to BIM which owns a detailed 3D model and comprehensive information on the physical and functional properties of the built assets [64]. This way, they can see each asset as an entity which includes history, condition, and estimated lifecycle. Strategies entailing integration of BIM and GIS in IAM involve ensuring interoperability between the systems. Developing data standards and protocols to facilitate smooth data sharing and involvement is part of this process [65]. Therefore, data from GIS like spatial location, terrain information, and environmental factors can be connected with BIM data made up of asset geometry, material properties, and maintenance records. Due to such interoperability, comes about better decision-making, an opportunity to view asset conditions in real-world scenarios, and make well-profound plans for maintenance and upgrades [66].

To augment BIM and GIS integration in IAM, the main mission is to enhance asset management knowledge during all stages of the asset life cycle. Utilizing BIM-GIS combined will enable companies to attain better and more exact asset inventories, better-informed predictive maintenance functionality, and efficient use of resources. On the other hand, the integration is meaningful also for the sustainable infrastructure development guides, which improve lifecycle assessments, energy efficiency analysis, the environmental impact evaluation during the planning and design phases [67]. Nevertheless, this combination in the practical world has to be succeeded by solid research and actual solutions, or in a less optimistic scenario, by some sort of proposal. A bibliometric analysis on BIM and GIS integration for infrastructure asset management, in 2020, showed that the smallest number of papers, only 16.6% accounted for the BIM-GIS integration and implementation for IAM. This can be justified by the very young age of this concept, considering the percentage of BIM and

GIS in IAM papers exhibiting 29.6% and 53.7%, respectively, which aligns with their historical development and eventual application [63].

BIM-GIS integration also poses certain challenges which have to be taken into account. One of the most significant problems is how to get around the trouble of combining disparate data sources, maintaining consistency, and keeping data accurate [68]. Issues of diverse data formats, standards, and poor quality levels [69] can make perfect data communication challenging. Consequently, there could be organizational constraints that come along as a result of siloed data management practices or a lack of specialized staff members in the given organization [70].

Nowadays, BIM-GIS healthy collaboration has brought in such innovations as cloud computing, artificial intelligence, and machine learning systems as a method of integration. These technologies facilitate the synchronization of up-to-date data as well as automate data processing through predictive analytics. It boosts decision-making support approaches using the IAM. BIM and GIS integration in the future is a priority area that is anticipated to focus on increasing the interoperability standards further, deepening data dimensions through AR and VR, and incorporating increased sustainability metrics in the asset management strategy.

Finally, the combination of BIM and GIS leads to huge notions of the transformation of IAM practices which include several channels such as the improved quality and performance of assets, development of resourceful and sustainable solutions as well as overcoming challenges through technological advancement. With more and more BIM and GIS applications gaining their adoption and development, the IAM of tomorrow is going to be an even more efficient, resilient, and eco-friendly doctrine for managing infrastructural assets.

2.6. Structural Health Monitoring (SHM)

In order to track changes in the geometric and material properties of engineering structures like buildings and bridges, a process known as structural health monitoring, or SHM, entails periodically sampling response measurements and observing and analyzing a system over time. Structures deteriorate with age and use in an operational setting. On a regular basis, SHM provides updated data about the structure's capacity to carry out its intended purpose. SHM is used for quick condition screening following extreme events, like blast loading or earthquakes. The goal of SHM is to deliver accurate information almost instantly about the structure's integrity. [71]

In the case of tunnels, SHM acts as a preventive method that will help to minimize the risk of structural failure in tunnels by offering real-time information. This activity can be dynamic, and it occurs both internally as a result of traffic loads and externally because of weather conditions among others. SHM systems, in particular, allow providing constant updates on the state of the structure and thus minimizing operational risks since the structure is monitored via sensors. Thus, for effective management of tunnel assets, SHM plays a key role in identifying problems at the early stage before these deteriorate to deformity, cracking, stress or even collapse. [72] [11] Contemporary SHM systems are commonly linked with decision support tools, where the collected data can be used for decision making by the asset manager. In addition, these systems do more than identify structural problems at an early stage; they also play a major role in enhancing the efficiency of tunnels as they undergo operational use, which enhances their safety and economic viability. [72]

2.6.1. Sensor-based monitoring systems

Sensor-based monitoring systems are a core element of SHM, providing continuous measurements and real-time updates. These systems vary from traditional such as contact-based sensors, such as fiber optic sensors, and non-contact sensors, such as LiDAR etc to the most novel ones. In the latest European Workshop on Structural Health Monitoring [11], some of the newly explored technologies mentioned in the collection of papers were: Nonlinear Ultrasonic Guided Waves, Wireless Sensing Systems, Acoustic Emission based, Optical and Computer-Vision based, Infrared Thermography based, Guided Waves based, Satellite Radar Interferometry based, Smart Self-sensory based, Ultrasonic and Electromagnetic Waves based, etc.

Nevertheless, in many Case-Studies explored in several papers, there is noted the major presence of monitoring systems such as: LiDAR Technology, Wireless Sensor Networks and Fiber Bragg Grating Sensors. LiDAR for example, offers an effective technique of observing and measuring tunnel structures without physical contact with the structure. It employs laser pulses to create a contour map of the tunnel wall and detect distortions with a high degree of accuracy. LiDAR systems have been especially used in deformation surveys of tunnels after construction, where the technique provides true 3D visual data to improve assessment of the structure's condition. [73] Wireless sensor networks, especially systems such as Ackcio Beam, are widely applied to Structural Health Monitoring (SHM) for tunnels. These systems eliminate problems associated with the wired solutions for instance require frequent access in underground facilities, as well as being capable of transmitting data in real-time. One such case is the Mass Rapid Transit (MRT) Tunnel in Singapore where Ackcio wireless nodes were integrated into the infrastructure to offer constant surveillance of the tunnel environment, thus minimizing the risks posed to workers who traditionally had to physically inspect the tunnels often with hazardous consequences for them. Thus, this approach enhances timely and accurate risk management practices without the time and monetary constraints of monitoring risks manually. [74] FBG sensors for instance often regarded as high-precision sensors for strains and temperature in tunneling applications. They function based on the variation in the wavelength of the reflected light, which is proportional to changes in the structure being monitored. FBG sensors are precise, immune to electromagnetic interference and quite amenable to the 'multiplexing' process for wide range sensing in large structures. These sensors are used in numerous systems used in tunnel SHM including the Wuhan Yangtze River Tunnel which tracks stress and deformity. [72].

Regarding such technological applications in the Italian tunnel infrastructure, it can be mentioned the significant European project of the Brenner Base Tunnel, which is undergoing construction and it is set to become the world's longest underground railway tunnel. This tunnel applies state-of-the-art fiber optic cables for Distributed Temperature Sensing (DTS) and Distributed Strain Sensing (DSS). These systems enable the monitoring of temperature fluctuations and mechanical pressure along the tunnel, necessary for assessing the structural integrity and safety during construction and during operation of the constructed object. [75]

2.6.1.1. Application in Tunnel Asset Management

Effective asset management of tunnels as important structures plays a significant role in safety, durability and functionality. Application of sensors for monitoring the behaviour of civil infrastructures has revolutionized the management of tunnels through acquiring data on structural status, environment and even potential hazards in the infrastructure. These systems are very useful in tunnels where it may be difficult to physically inspect the area or it may be too costly. Below are key ways sensor-based systems are applied in tunnel asset management:

- Real-time SHM
  Sensor-based SHM systems are widely deployed in tunnels to continuously assess their structural integrity. These systems incorporate different instruments including the strain gauges, the fiber optic cables, the tilt meters and other devices in detecting orientation alteration, pressure, and mechanical distortion in the tunnel. Recalling the

example of the Brenner Base Tunnel mentioned in the previous section where fibers in cables used to monitor strains and temperatures along the body of the tunnel. This data makes it easier to identify signs of structural failure like cracking or deformation and take corrective action before collapse happens. [75] [76]

- Environmental monitoring

  Tunnels, especially those in challenging environments, are susceptible to changes in temperature, humidity, and gas levels. These parameters are known to be monitored by the use of piezometers, temperature sensors together with the gas detectors which run on a continuous basis. For instance, temperature monitors in the Brenner Base Tunnel pick a slight fluctuation that can imply heat or fire hazards. Likewise, piezometers measure inflow of water into tunnels with a view of avoiding floods or structural erosion. [75] [76]

- Automated data management and alerts

  The use of IoT technologies in interaction with SHM it is possible to eliminate manual data collection and processing and deal also with issuing of alerts. In systems such as those offered by Move Solutions, wireless sensors measure tunnel vibrations, stresses, and other environmental inputs and send the information to a common hub. It is on these platforms that the data is analysed and the asset managers immediately receive the alert once the set thresholds are crossed to enable them to respond appropriately concerning the maintenance of the assets. [77]

- Maintenance planning and lifecycle management

  Another advantage of sensor-based monitoring is its capability to perform the so-called 'predictive maintenance'. One of the main challenges of using such sensors is in obtaining constant stream of data when compared with traditional periodic manual inspections which are disruptive and expensive. Its effectiveness is realized through minimizing frequencies of the tunnel maintenance period hence increasing its usage time. Equipments advertised by Encardio Rite suite of Tunnel Monitoring Instruments which count extensometers, inclinometers, and strain gauges have been used in long term projects as these factors indicate movement of soil, tunnel deformation for maintenance that can only be conducted on as and when basis. [76]

- Safety and risk management

  Some monitoring sensors come in handy in minimizing the frequency of inspections by human beings, which reduces the exposure of such workers to dangers. Through the use of wireless sensors that relay data in real-time like the previously mentioned MRT tunnels in Singapore and the Brenner Base Tunnel, operators are able to observe the state of the tunnel through means such as video feeds and access to the actual environment where the risk like a slide or high load bearing pressure can be assessed without the need of personnel to physically enter the location. [73] [75]

In conclusion, the decentralised, sensor-based concept of asset management in tunnel infrastructures facilitates the transition from a reactive fire-fighting approach to maintenance to a proactive and even predictive one. Through collecting real-time ambient data, utilization of auxiliary robotics, and IoT affordances, the tunnel operators will not only be best placed to monitor and expand on the safety, functionality, and service life of these paramount structures but also achieve maximum cost optimization and least human exposure.

As much as researchers have advanced in the field of SHM technology, there exist several voids. Owing to the complexity of tunnels, the major drawback of the proposed approach is the relatively high cost of implementing high-end sensor networks for monitoring these infrastructures. The costs are relatively high meaning that these systems are not easily adopted especially for older tunnels that are not inherently equipped with such systems.

One other major weakness is absence of consistency in SHM practices. While fibre optic and wireless sensors have been used successfully in many case studies, there is no specific blueprint on how these can be applied and that is why they are not easy to replicate across projects and regions. This lack of standardization also makes analysis of the collected data challenging and may produce highly irregular outcomes.

To build upon this work, future research should aim at decreasing the cost of implementing SHM systems while maintaining accuracy. One proposed strategy is the inclusion of machine learning algorithms on top of the SHM data with a view of achieving failure pattern prediction and maintenance schedule optimization as suggested by several authors. Moreover, the emergence of internal wireless SHM systems that do not require the laying of extensive communication channels for monitoring in real time could substantially improve the availability of these systems.

3. Conceptual framework of IAM

IAM harmonizes between operational requirements, advanced planning and control, and other essential financial and business measurements with concerns to the functionality, safety, and durability of assets. The framework addresses the lifecycle of infrastructure assets, taking into account changing conditions and needs of society, as well as maintaining sustainability and resiliency regarding risks such as climate change. [1] [78]

3.1. Concepts and definitions

IAM integrates strategic direction in planning, systematic engineering, and effective financial stewardship throughout the service life of infrastructure assets. [1] This makes it more of a sustained business oriented value approach that looks at operational needs for the present as well as the greater value of increase in the overall product lifecycle whilst factoring into account predictive models that are blended with real-time analytics for purposes of decision making with regards to the same. [79] The IAM in the transportation sector comprises the properties of roads, tunnels, bridges, and railways together with different service demands and deterioration rates. In IAM, the concept of "value" goes way beyond the business value, it includes environmental and societal value. This externally focused conceptualisation of asset value provides a way of linking IAM outcomes with wider social and environmental goals such as emissions reductions, safer roads, and better-connected cities. [1] This value-driven approach is to respond to the diverse and multifaceted needs of infrastructure systems: for this purpose, IAM frameworks incorporate interdisciplinary methods such as the lifecycle cost analysis, risk evaluation and, resilience planning. [78] [80]

3.2. Standards and regulations

The IAM framework's foundation must include a consistent approach, and adhering to protocols helps achieve this. IAM has its roots in international standards such as ISO 55000 and PAS 55, which encourage organizations to converge their approaches and follow a consistent structure worldwide [81] These standards promote preventive maintenance, continuous monitoring, and analytical decision making whereby the asset managers are prompted to take early action before a problem arises [78]. However, to ensure that IAM is implemented in a way that will effectively address the infrastructure requirements of the different sectors, more specific regulations are developed. For instance, AASHTO's guidelines are briefly as follows; AASHTO guidelines stress measures on safety and performance indicators relevant to transportation systems in the United States; these metrics factor in the intricacy and densely populated urban transport systems. [78] For the last few years, the Europe directives integrated climatic adaptation and resiliency into the IAM regulatory approaches, pointing out that IAM frameworks must consider the rise of maximum intensity extremity weather incidences and other climatic shocks. [79]

Other processes, including policy change or procurement reforms, also influence IAM practice to a great extent. For instance, both Australian and European policies have extolled teamwork or collaborative procurement systems in large-scale infrastructure project delivery as a way of freeing up traditional procurement systems from excessive burden in handling project complexities. These partnership models, for instance, Public Private Partnerships (PPPs), seek to establish the project goals and objectives consistent with public interests such as; environmental conservationism, economic diversification among others. [80] Such congruence of policy, regulation, and practice is important so as to ensure that the proposed IAM framework apart from meeting technical specifications, also aligns to social utility.

3.3. Lifecycle of assets

IAM's lifecycle management perspective covers each asset phase: acquisition, planning, operation, maintenance, planning, and disposal. This approach makes it easier to conduct an orderly evaluation of the maintenance requirements, capital costs, and operating changes required throughout an asset's life cycle. [1] Using the lifecycle approach eliminates early asset failure and oversees the likelihood of random downtime as the technique allows for maintenance to be accomplished based on historic and current data. [80] Transportation applications are especially suitable for the lifecycle approach since they involve extensive usage, varying climates, and various forms of wear on structures. Methods like Markov chain and MCDA are used to analyze deterioration rates, resource requirement, and time of intervention needed in clients' care. [82] As these models identify and rank the assets based on their risk level, asset managers are better placed to target the areas that really require their attention hence preventing hasty and expensive repairs.

The IAM process also takes into account external environment and socio-economic effects of infrastructure assets. For instance, the resilience planning considers the effects of climate change, encompasses measures to counter balance the effects of events such as floods, storms, and heat and which hasten asset deterioration. Risk based models are therefore employed in lifecycle strategies, which attempt to estimate both short and long term risk to the stability of the assets and recommend changes to the design and maintenance practices. [1]

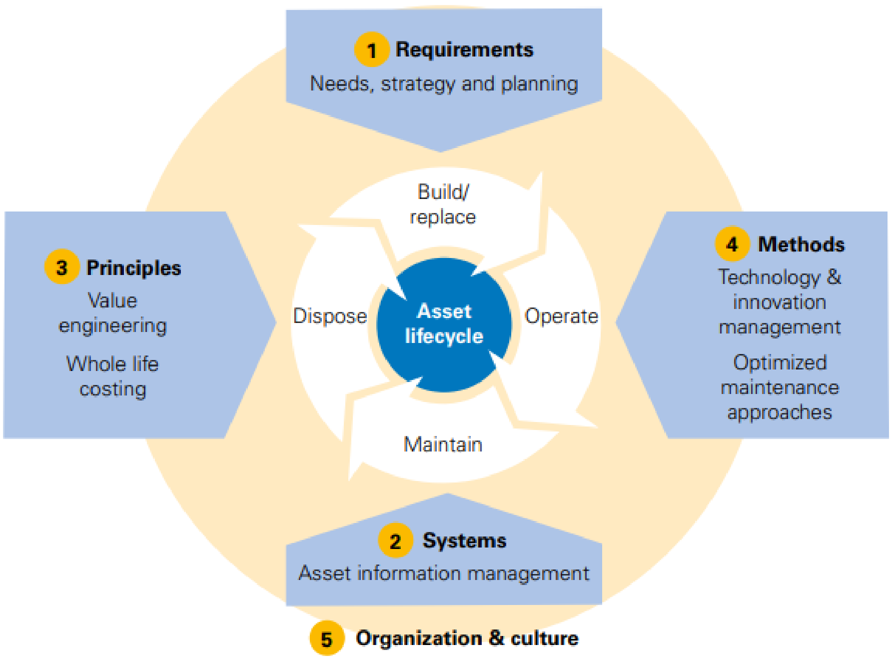


Figure 4. Holistic approach to asset management transformation **[60]**

3.4. Challenges

Implementing IAM within the transportation sector presents numerous challenges, ranging from financial constraints to data management complexities. The following are some of the most prominent obstacles:

- Funding Limitations: Transportation IAM calls for huge investment in data acquisition, processing and the applications of contemporary technologies. But here funding constraints become a big issue and the more sophisticated IAM solutions that are often employed, can be prevented from being implemented, thus the assets are kept for long without proper maintenance and therefore they just wait to fail. PPPs have been identified as critical in providing sourcing solution to the funding deficit with regards to the project. For example, use of collaborative procurement strategies within large Australian infrastructure projects has seen entities work together to spread risks and returns for financial and operational loads, which has improved the sustainability of assets as well as their recurrent maintenance and upgrades. [80] However these models need policy that ensure sustainability of projects by linking public benefit and profitability so that projects remain high performing without/ risking accessibility and safety.
- Standardization Issues: The absence of coherent procedures that can be adopted for all the areas implies certain discrepancies in the management of assets. To some extent,

the same can be said of ISO 55000 and PAS 55 where localized implementations and inconsistent usage result into difference in performance evaluation and maintenance regimes. [78] For instance, the European Union has enhanced the IAM practices by directing guidelines that support conformity in climate change adaptation measures and asset management approaches. However, much broader standardization activities are required for more effective IAM practice implementation in different regions, as well as necessary for data exchange and asset performance benchmarking. [79]

- Data and Technological Integration: The modern structures of IAM systems are partially technology-dependent due to data processing and analysis. It has been difficult to integrate BIM, GIS, and IoT with sensors while experiencing expensive costs and a lack of availability of skilled employees. [80] Further, data accumulated by these systems needs to be stored, processed and analysed securely and this inturn put the system at risk for data breach and further calls for enhanced security measures. Some IoT and GIS integration can be operational problems because the two need to transfer and analyse data quickly to support decisions about infrastructure asset management in real time. [81] These tools are very informative in presenting the state of the assets and usage patterns to the asset managers but to implement it needs substantial investment in technology and manpower.
- Complex Interdependencies and Risk Management: In part, the assets relate to the transportation systems which comprise a complex system of a network where the failure of one element affects the others. For instance, an adverse event in a large tunnel can lead to congestion in an entire city thus a lot of time and resources would have been lost. IAM frameworks have to align with sophisticated risk management approaches that factor in such dependencies and expends efforts to avert such extensive disruptions. [79] An example is residue risk evaluation, whereby an organization assesses an assets' readiness for different incidents depending on the strategies that have been put in place such as natural calamities, and effects of climate change. The use of both risk assessment and key risk indicators, as well as predictive and resilience models, enables the identification of not only the existing risk levels but also to use the assessment to look for future risks that infrastructure assets need to respond to – this guarantees flexibility to the infrastructure assets [1] [80]

4. Sensor Integration in tunnels in service of TAM

4.1. Gap identification in the field and conceptualisation of the proposal

Effective incorporation of real-time sensors corresponds to the biggest potential for developing the GIS and raising its stakes as a decision support system a notch higher. Though actual real-time sensor data are not present in the current thesis, a structure on how it can be incorporated is presented to demonstrate the capability of the system.

The idea of incorporating GIS and IoT, to build a proposal that actually can serve the stakeholders, was identified after an extensive review of the present material and current developments and when such interoperability wasn't seen. It does not only, as it has been mentioned, hold a great power to change the decision-making process, but it's not an isolated proposal, which means it can be used in the future as the initial step of a bigger project that might increase in application fields, monitored parameters and construction phases.

4.2. Types of sensors for tunnel monitoring

To be able to allow the reader a greater understanding and visualization of the sensors and the project, some of the most used and common types are presented below, along with their qualities.

- Temperature Sensors: Initially, temperature changes inside tunnels: it facilitates supervision of environmental conditions and overheating problems within the tunnels.

Thermocouples*

1. No resistance lead wire problems
2. Fastest response
3. Simple, rugged
4. Inexpensive
5. High temperature operation
6. Point temperature sensing

1. Non-linear
2. Low voltage
3. Least stable, repeatable
4. Least sensitive

* https://www.processparameters.co.uk/what-is-a-thermocouple/

https://www.watlow.com/resources-and-support/engineering-tools/knowledge-base/temperature-sensors-comparison-guide

Resistance Temperature Detectors (RTD)*

1. Most stable, accurate
2. Contamination resistant
3. More linear than thermocouple
4. Area temperature sensing
5. Most repeatable temperature measurement

1. Current source required
2. Self-heating
3. Slow response time
4. Low sensitivity to small temperature changes

* https://www.auxitrolweston.com/products/temperature-sensors/platinum-rtd

https://www.watlow.com/resources-and-support/engineering-tools/knowledge-base/temperature-sensors-comparison-guide

Infrared Sensors*

1. Non-contact measurement
2. Close range accuracy
3. Low power consumption
4. Secured communication
5. Compact size and affordability
6. High repeatability

1. Environmental sensitivity
2. Single device control
3. Line of sight dependency
4. Lower data transmission rate

* https://www.solutionsdirectonline.com/raytek-hi-temp-infrared-temperature-sensor-with

https://www.geeksforgeeks.org/advantages-and-disadvantages-of-infrared-sensor/

- Humidity Sensors: Indices to detect moisture levels that might pose a threat to the building structures in the course of its use.

Capacitive Humidity Sensors*

1. Withstand negative temperature
2. No maintenance need for longer periods
3. Flexibility to use
4. Atm. pressure independent

1. Limited long term stability
2. Sensitive to dewing and certain aggressive substances

* https://shop.bb-sensors.com/en/Measurement-by-branches/Medical-Technology-Pharmacy/Capacitive-humidity-sensor-KFS140-D.html

https://www.rfwireless-world.com/Terminology/Advantages-and-Disadvantages-of-humidity-Sensor.html

Digital sensor platform*

1. Measures both humidity and temperature
2. High accuracy
3. Compact design
4. Wide operating range
5. Low power consumption
6. Fast response time

1. Costly
2. Limited environmental protections
3. Requires precise installation

* https://sensirion.com/media/documents/33FD6951/6555C40E/Sensirion_Datasheet_SHT4x.pdf

- Vibration Sensors: Measuring certain levels of structural deformations that might signify onset of stress or damage.

Piezoelectric accelerometers*

1. High sensitivity
2. Rugged construction
3. Wide frequency range
4. Stable performance
5. High Signal-to-Noise ratio

1. Costly
2. Environment sensitivity
3. Signal conditioning needed
4. Fragile crystal material
5. Uniaxial direction

* https://www.asc-sensors.de/en/sensoren/asc-p101a15-en/

- Air Quality Sensors: Measuring gases such as CO, NO, NO2 etc. important for safety and conformity with the standards set by health and environmental protection agencies.

Electrochemical Gas Sensors*

1. High selectivity (many specific gases)
2. Compact and reliable
3. Low power consumption
4. Easy handling
5. Wide measurement range

1. Short lifespan
2. Calibration required
3. High investment costs

* https://www.durag.com/en/gas-monitoring-2268.htm

In the Sensor Technologies for Civil Infrastructures, the chapter “Sensing solutions for assessing and monitoring tunnels” introduces the most common sensors used for the monitoring of tunnels as presented in the tables below. Their selection is directly related to the location of the tunnel as the challenges depend on it and the parameter to be measured as different sensors are designed to perform different functions. [83]

Sensor	Measurement application	Estimated accuracy	Approx. cost[a] (GBP/USD)
Borehole extensometer	Movement of one point in the soil/rock/tunnel relative to another point	~0.02 mm	£1000/$1200
Convergence gages	Change in dimension (e.g., ovaling of a tunnel)	~0.02 mm	£1800/$2200
Crack gages	Relative movement across a crack	Manual: ~0.5 mm Electronic: ~0.01 mm	£10/$12 £250/$300
DEMEC gages	Movement across a crack	~0.01 mm	£400/$500
Electro level	Differential settlements/ inclination	~0.1 mm/m	£200/$250
Fiber optic piezometer	Water pressure	~1 kPa	£600/$750
Fiber optics	Distributed strain and displacement	BOTDR: ~50 microstrain	£50k/$60k (analyser) Cable cost varies
Fixed extensometer	Displacements relative to a fixed point including tunnel walls relative to the surrounding soil, convergence, and surface points	~0.02 mm	£1900/$2300
Image analysis	Noncontact measurement of crack widths, relative displacements and strain fields	~0.01 pixels (physical displacement requires a scale factor)	Varies depending on system
Inclinometers	Change in inclination/ rotation of an object	~10 arc sec.	£4000/$5000
In-SAR	Displacements	A few mm	Service contract
Instrumented rock bolts	Strain (and stress) in anchors	~1 microstrain	£450/$550
Liquid level	Differential settlements/ inclination	~0.3 mm/m	£1100/$1350
Multipoint extensometer	Probe, rod, and borehole extensometers that have multiple measurement locations	Varies	£2000/$2500

Open standpipe piezometer	Water pressure	~10 mm	£50/$60
Pneumatic piezometer	Water pressure	~1 kPa	£100/$120
Pressure cell	Soil pressure—horizontal pressure for spade-type pressure cell	~0.1 kPa (depending on total range)	£400/$500
Probe extensometer	Relative displacement of points in the soil	~2 mm	£350/$425
Reverse head extensometer	Extrusion of the tunnel face/relative displacement	~0.5 mm (depending on total range)	Not available from all sensor suppliers
Rod extensometer	Displacements relative to a fixed point	~0.02 mm	£1750/$2150
Sliding micrometer	Extrusion of the tunnel face/relative displacement	~0.002 mm/m	£500/$600
Total station and targets	Used to measure the displacement and rotation of tunnel linings and surface infrastructure	Distance Reflectors: ~1 mm Reflectorless: ~2 mm Angles: ~1 arc second	Total station: £2.5 k and up $4 k and up
Vibrating wire strain gage	Strain measurement in structural members (vibrating wire strain gages are used in a variety of applications)	~1 microstrain	£80/$100
Vibrating wire piezometer	Water pressure	~0.1 kPa	£350/$425
Wireless sensor networks	Various including: strain, displacement, inclination, temperature	Varies	£500/$600 (per node)

Figure 5. Available sensors for tunnel monitoring **[83]**

4.3. Sensor placement strategy

Sensors are strategically positioned at critical stress points such as the crown, walls, and joints for measurement of deformations, stress, and formation of cracks. Structures of high traffic density or those which are frequently exposed to the concentrated loads also become prime candidates for vibration measurement of the structure. In addition, sensitive areas where there is potential for soil liquefaction, fault or drain water seepage are equipped with sensors. Internal and external factors including humidity and temperature as well as quality of air are essential in installation of sensors. Humidity and water leakage sensors are placed at areas most affected with moisture while air quality sensors are placed at areas of prevalent air flow such as near exits, midpoints and areas of low air flow. Temperature control areas, usually situated close to electrical apparatus or luminaires, use thermal infrared cameras and several temperature sensors such as thermocouples and thermal imaging systems. Security-sensitive areas or paths like hall escape routes, fire exits, and evacuation zones are kept safe and assessable to the environment. Likewise, the sensors are installed in the areas that are at risk of fire like the areas around electrical activities to detect any signs that indicate the presence of fire risk.

However it is important to note that the sensors are placed strategically based on the importance of the region of the tunnel, but they are also randomly placed uniformly throughout the tunnel to ensure comprehensive data collection across all regions, including less critical areas.

In Figure below it is presented a complete solution for monitoring in a tunnel environment by **Leica** [84] and its legend.

- **A** Wireless smart data hub for geotechnical sensors
- **B** Geotechnical sensor data import into Leica GeoMoS via AnyData
- **C** Wireless sensor distance & tilt measurement for convergence/compression
- **D** Wireless sensor tilt with beam measurement for longitudinal profile settlement
- **E** Wireless sensor tilt with beam measurement for ovalisation measurement
- **F** Wireless interface with locally connected crack gauges
- **G** Wireless interface with locally connected water level sensor / in-place inclinometer

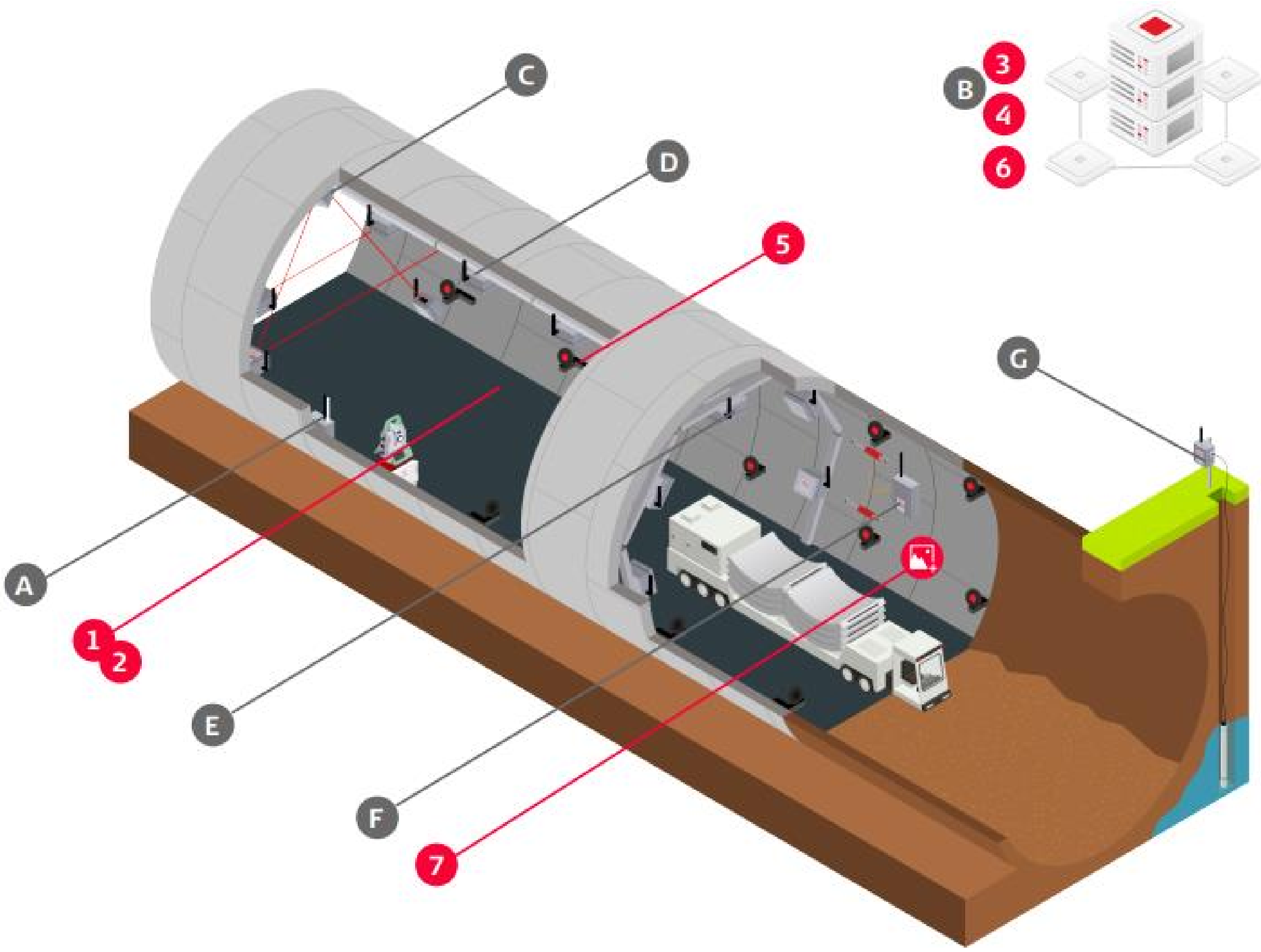


Figure 6. Integrated monitoring solution for tunnels as proposed by Leica

Video Illustration of the sensor placement

4.4. Parameters to monitor and their relationship to the stakeholders

As explained above in this thesis, the aim is to monitor key parameters so as to guarantee safety, functionality as well as sustainability of the tunnel infrastructure. The four primary parameters proposed for monitoring are:

1. Temperature
2. Humidity
3. Vibrations/Displacements
4. Hazardous gases

In the monitoring of these parameters lays the ultimate goal of the thesis; serve to multiple stakeholders in an innovative, yet user-friendly way.

1. **Regulatory authorities**
   - Compliance and adherence to safety and environment standards.
   - Supervise compliance with operational processes for maintaining public and worker security.

2. **Emergency response teams**
   - Depend upon and utilize actual-time information for an immediate response in the event of the fire or release of hazardous gas.
   - Enhance the organization in evacuations and prevention measures.

3. **Infrastructure owners and investors (government and/or private)**
   - Reduce risks associated with operational downtime and infrastructure failures.
   - By the assessment of monitoring information, evaluate the value of assets and determine where and when to invest.

4. **Research institutions and consultancy teams**
   - Use data mapping approaches for long-term more permanent structural damage and environmental conditions analysis.
   - Create effective strategies to improve assets performance and safety.

5. **Operation and maintenance teams**
   - Allows for coordination of scheduling for maintenance of facilities and efficient utilization of human resources and apparatus.
   - Anticipative monitoring also avoids potential failures, and this conditions that the processes will keep running in the best possible fashion with the least possible interruption of service.
   - Targets specific sectors for observation; minimizes overall checks and concentrates on high-risk regions or areas.

6. **End users**
   - Service Reliability: Reduces the frequency and degree of interruptions to the operation of the tunnel and allows the tunnel to be continually used on a day-to-day basis.

- Public Trust: Boosts the confidence of the users in the safety and efficiency of the infrastructure, translating to more usage and satisfaction.
- Enhanced comfort and smoother experience

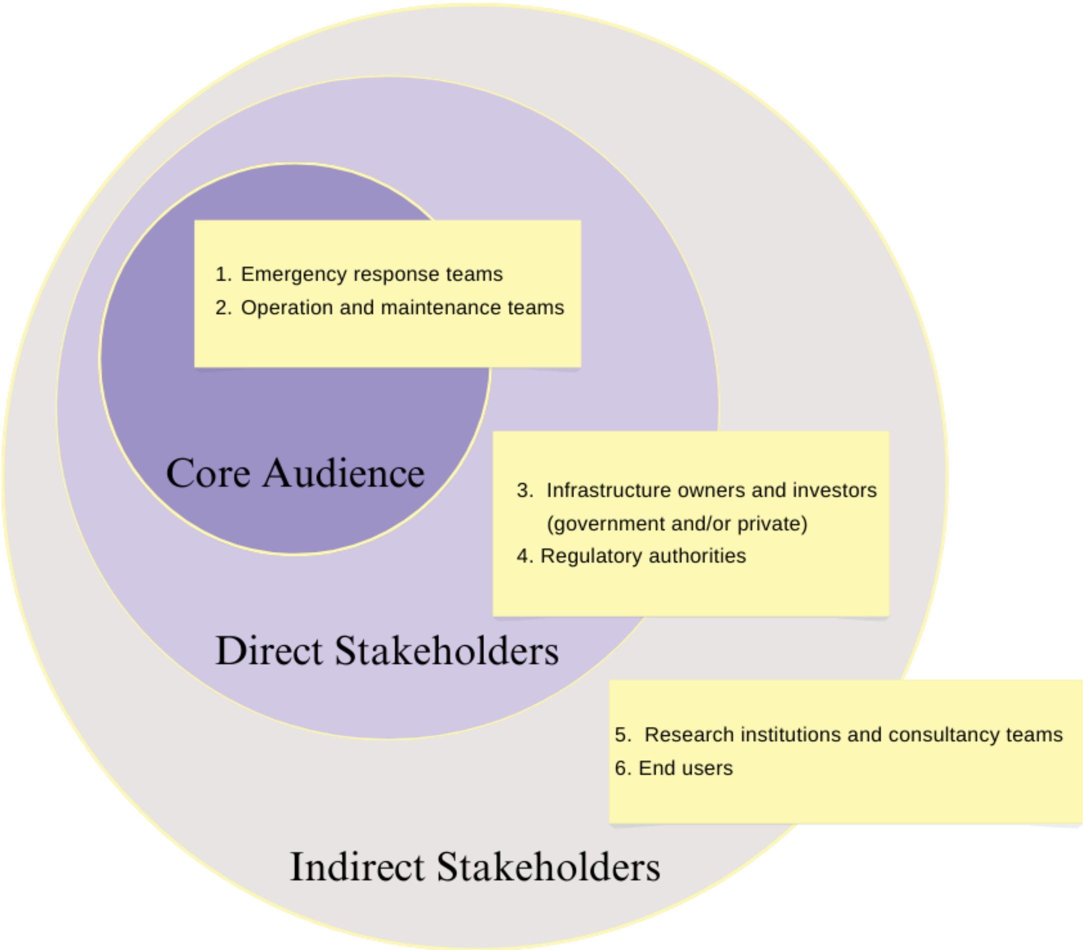


Figure 7. Classification of the stakeholders based on how the solution affects them

The stakeholders are classified into Core Audience, Direct Stakeholders, and Indirect Stakeholders depending on their direct involvement, level of control over the tunnel monitoring system, and direct interaction, respectively. Core users encompass individuals who play an immediate and tangible role in utilizing real-time data such as the emergency response team and the maintenance crew. The direct stakeholders are those who control the physical infrastructure of the tunnel; the owners and investors, the management team, and the relevant authorities. Indirect Stakeholders are individuals, organizations and related entities who have no direct involvement with the daily functioning of the system, yet are impacted by it such as end users and research organizations. This division helps maintain awareness of the way each stakeholder is affected by the proposed solution and how they relate to the monitoring of the tunnel.

4.4.1. Fields of application

The four parameters contribute in various ways for the stakeholders and this is explained in the following paragraphs, separately for each of them.

Temperature monitoring plays an important role in the protection of structures from extreme weather that may otherwise cause deterioration to the tunnel structure and the materials used. The Emergency Response Teams can benefit from the temperature data in evaluating the risks of fire and in managing heat-related emergencies. The O&M Teams favour temperature measurements to identify the probabilities of failure in the tunnel systems inclusive of HVAC or electrical installations. The recorded data is essential for Regulatory Authorities to ensure there is compliance with safety standards of operating temperatures, preventing hazardous conditions. Infrastructure Owners and Investors are benefited with temperature data to maintain the longevity of the tunnel without any unexpected failure and costly repairs. The Research Institutions and Consultancy Teams can use the data for staking the structural analysis that can be applied for contributing towards the strategies that can enhance the presence of tunnels and strengthen its resilience in the times of greatly changing climatic conditions. Lastly, indirectly affected parties under this aspect are the End Users as temperature has very little to do with their comfort while in the tunnel particularly during weather extremes.

As such little or lack of attention towards **humidity** measurement may expose such structures or areas to moisture accumulation that results in corrosion, mold formation or weakening of such structural member/segment, so the monitoring of this parameter is also crucial. Emergency Response Teams employ humidity data in order to assess risks concerning fire or flooding. Operation and Maintenance Teams can schedule preventive maintenance activities to perform maintenance tasks, including sealing off water leakage or dehumidifying parts which tend to have high humidity. In situations where climate conditions are controlled, Regulatory Authorities have an interest to monitor humidity in order to maintain health and safety standards concerning the quality of tunnels through air and protection of structures from deterioration. Infrastructure Owners and Investors stand to benefit from understanding these trends in Humidity since it directly impacts on the durability of the infrastructure assets and informs when to invest in upgrade or repairs. The management role of Research Institutions and Consultancy Teams can assess long-term environmental effects on the tunnel's structural health, contributing to more sustainable tunnel management strategies. End

Users are also influenced by humidity levels since high humidity can later make the environment uncomfortable and is associated with potential health risks.

Vibrations/Displacements: Monitoring vibrations and displacements is vital for identifying shifts in the tunnel's structural integrity that could signal potential failure or danger. Emergency Response Teams take advantage of these acquired vibration and displacement data to accurately determine the extent of damage during events such as earthquakes, or tunnel collapses responding and evacuating faster. Operation and Maintenance Teams monitor these parameters to detect subtle movements or unusual vibrations that could indicate potential structural issues, allowing necessary correcting actions could be undertaken before any serious structural problems emerged. Regulatory Authorities especially can make use of this data to verify that the tunnel meets safety requirements especially as it concerns the structural response and behaviour over time. Infrastructure Owners and Investors find vibration and displacement data valuable for assessing the tunnel's durability to understand the deposition, integrity and regularly require major refurbishments on the tunnel thereby preserving their asset and investment. Research Institutions and Consultancy Teams can rely on vibration data to study the tunnel's long-term behaviour when subjected to dynamic loads, establish structural enhancements and innovative design. Whereas for the end-users, such displacements rarely pose any real importance, as they are of an imperceptible value typically, unless the tunnel is located in an area of particular seismicity where displacements are of a higher magnitude and can be perceived by humans.

Monitoring hazardous gases, is crucial for the safety and health of tunnel users and personnel. (In this thesis the focus will be on the carbon monoxide (CO) just for the sake of simplicity.) ERT teams require constant and accurate measurement of the concentration of toxic or combustible gases to respond appropriately and effectively. Operation and Maintenance Teams monitor and control levels of Gas to check the presence of hazardous rates, correct functioning of ventilation systems as well as checking the efficiency of the filtration systems. Regulatory Authorities ensure that concentrations of the hazardous gases produced as products are within definable levels that are allowed by the laws governing occupational health and safety. The respective business stakeholders of Infrastructure Owners and Investors regard gas data as significant in the purpose of mitigating with risks, responding to liabilities, and keeping the tunnel continually functional and secure for public access. Research Institutions and Consultancy Teams can study hazardous gas patterns to propose improved methods of ventilation and safety measures that will indicate improved long term safety of tunnels. Most importantly, gas monitoring immediately relates to End Users since this process concerns their safety and health when using a tunnel; accurate gas monitoring promotes trust in the tunnel's condition and a more comfortable experience of a tunnel.

4.4.1.1. Special focus in Operation & Maintenance

Among the list of the multiple stakeholders which this thesis proposal aims to facilitate, the core one is the operation & maintenance division. These teams play a central role in tunnels asset management since they are the one who makes sure that the functional and physical condition of tunnel is effective, safe and efficient during its entire life cycle. However, they face numerous challenges:

- Limited real-time data: Unfortunately, O&M teams tend to utilize traditional inspection techniques, making the detection of specific issues occur only during scheduled intervals or through rigid reporting formats.
- Inefficient maintenance scheduling: Maintenance is often corrective; this involves responding to problems as they occur making it costly than preventive, hence frequent tunnel disruptions.
- Resource constraints: Inefficiency stems from the poor monitoring and nonexistence of better tools to predict the allocation of these resources.
- Fragmented communication: The various stakeholders in O&M operations mostly incorporate various systems that fail to integrate to enable enhanced coordination between O&M teams and the various stakeholders.
- Safety Risks: By not being able to obtain information in a timely fashion, it becomes even more dangerous for the various teams that would be in charge of inspecting and repairing such infrastructural sites as during emergencies.

The integration of GIS-based sensor systems into tunnel asset management offers transformative solutions to these challenges:

- Real-Time Monitoring: The strategically placed sensors all over the tunnel enable the continual collection of data on factors that are essential to the tunnel's structural health, environmental conditions and traffic patterns.

- Centralized Visualization: Such real-time sensors are processed by GIS platforms whereby the O&M teams can identify the geographical location of the tunnel condition. This spatial representation helps in discovering areas of additional attention.
- Predictive Maintenance: Combined with data obtained by sensors, the use of Predictive Analytics allows teams to forecast problems before they occur, thus changing from a reactive to preventive maintenance approach.
- Enhanced Coordination: Maintenance information shared through GIS dashboards facilitates the collection of information from other stakeholders and makes it easier to coordinate on the goals and tasks set for maintenance.
- Improved Safety: Timing alerts and accurate place information decrease dangers for workers, enhancing security and performance.

Additionally, the proposed framework ensures continuous improvement by incorporating feedback from O&M stakeholders:

- User-Centric design: By scheduling and conducting workshops, and feedback meetings with O&M staff, the GIS dashboard is fine tuned in order to meet the operational requirements.
- Adaptability: The framework is extendable, enabling the addition of new sensor types as well as new analytical tools as the technology develops.
- Stakeholder collaboration: Due to the proactivity of the communications, the framework ensures that O&M is in harmony with the broader goal of asset management.

This proposal fills the gaps by focusing on how we can meet the needs of O&M stakeholders to improve their effectiveness with a view of achieving a seamless synergy with other players. The herein outlined GIS-based framework for tunnel asset management can be succinctly described as a complete paradigm shift in the practical function of O&M teams. That way it is easier to allocate resources from the real time data visualization hence it is easier to ensure that important areas of concern are attended to in the shortest time possible thus cutting down on wastage and increasing efficiency.

The application of regular, preventative maintenance, based on predictive analysis slashes costs and increases asset durability while efficient scheduling reduces operating time.

Hazardous conditions that can affect the worker are detected early through the use of sensors hence averting dangerous working conditions. In addition, through the use of a common GIS, the framework enables O&M teams and other users to communicate effectively thus improving decision making and response times.

Besides addressing current issues, such approaches also establish a high standard of tunnel asset management and effective organisational practice of stakeholder involvement and improvement of efficiency.

The end product is a flexible, scalable solution that allows O&M groups to efficiently respond to today's infrastructure management needs.

4.5. Sensor integration evaluation - Advantages and Disadvantages

The application of sensors in the tunnel asset management can be viewed as an innovative way to address the operational, safety, and efficiency factors of infrastructure management, as it has been already pointed out. Due to the real-time data, the ability to view equipment condition and predict a failure, as well as more effective communication with the stakeholders, the integration of sensors helps to overcome various problems associated with conventional infrastructure monitoring systems. Although, similar to most technical solutions, this approach is not without some drawbacks.

In order to offer the balanced perspective of the successes and challenges of sensor integration in light of these potential impacts on tunnel asset management system, this section assesses the pros and cons of sensor integration.

Table 1. Advantages and disadvantages of sensor integration

Category	Advantages	Disadvantages
Operational Efficiency	✓ **Real-time monitoring**: Continuous data collection ensures immediate awareness of structural and environmental conditions ✓ **Predictive maintenance**: Early detection of issues allows for preventative measures, reducing disruptions	× **Data overload**: High volumes of data may present the need for more elaborate analysis tools, or the need for highly qualified personnel to interpret

Cost Implications	✓ **Reduced maintenance costs**: Predictive analytics help to avoid emergency repairs and increase the useful lifetime of the assets ✓ **Resource optimization**: Focused maintenance activities lead to better allocation of manpower and materials	✗ **High initial investment**: Deployment of sensors as well as the establishment of a GIS platform entails substantial upfront costs
Safety	✓ **Hazard detection**: The use of early warning systems minimizes the risks to the workers and users of the created infrastructure	✗ **System failures:** Sensor malfunctions or problems in communications have the potential to compromise monitoring efforts
Stakeholder Collaboration	✓ **Improved communication**: Stakeholders are able to access data and information on shared platforms where necessary for decision-making	✗ **Integration complexity**: The presence of numerous stakeholders and multiple systems alignment translates into a challenging interoperability
Scalability and Adaptability	✓ **Scalability**: Opportunity into system evolve by adding new sensor types and expanding infrastructure coverage ✓ **Adaptability**: Such flexible frameworks allow the incorporation of thriving technologies such as ML and AI	✗ **Technological dependency**: Relying entirely on technology increases the system's vulnerability due to cybersecurity threats and technical outages
Data Accuracy and Insights	✓ **Precision**: Sensors allow highly accurate measurements, specific to location	✗ **Data calibration needs**: Regular calibration or replacement of sensors is required to maintain accuracy and this can be resource-intensive
Environmental Impact	✓ **Eco-friendly solutions**: Optimizing the use of resources, in the long run leads to a reduces carbon footprint in the O&M	✗ **Electronic waste**: Replacement and disposal of sensors may impact the environment negatively if there's no sustainable management

5. Building the GIS

The creation of a Geographic Information System (GIS) forms the backbone of this thesis, offering a foundational platform for visualizing, analysing, and managing tunnel infrastructure data. A GIS allows the depiction of tunnel galleries and their coordination with other transport systems, and the use of various apparatus to support decision-making based on accurate information layers. In this chapter, the procedures for constructing the GIS are outlined, including the gathering and conditioning of data, as well as the representation of data in ArcGIS Pro and the possibility of incorporating live sensor information. By leveraging the capabilities of GIS, this study not only aims to offer a detailed representation of tunnel infrastructure but also to pave the way for advanced monitoring and predictive analysis that can significantly enhance stakeholder engagement and decision-making processes.

5.1. Data collection and preparation

Only well-prepared and systematically accrued data can form a solid foundation for a highly effective GIS. In this context, it should be noted that the collection of the core data for this thesis was conducted from different sources that are closely connected with interdisciplinary character of the work. This data includes:

- **Tunnel gallery information**: Entrance and exit points of tunnels, with their geographic coordinates and unique identifiers (e.g., gallery names).
- **Road network data:** Layers representing the transportation network, critical for contextualizing the tunnel infrastructure and understanding its connectivity within the broader system.

This data was sourced from:

1. Materials provided by the thesis advisor, which included detailed road network shapefiles.
2. Course materials from the elective lecture GIS for City and Land, which offered supplementary layers for broader analysis.

5.2. GIS creation in ArcGIS Pro

The first step involved ensuring that all spatial data was referenced using the appropriate coordinate system for Italy to maintain spatial accuracy and alignment with national datasets.

The ArcGIS Pro project environment was configured to use the WGS 84 coordinate system via the *Map Properties > Coordinate System* tab. While utilizing the most popular geographic coordinate system, WGS 84 integrates well with other data sets and can be used in the future when needed, without additional transformations.

The tunnel data was initially organized in an Excel table, structured with the following columns: Location, X coordinate, Y coordinate. This table was saved as a CSV (Comma Separated Values) file for compatibility with ArcGIS Pro. The CSV file was then imported into ArcGIS Pro using the *Add Data* tool. During this process: The X field was located by Longitude, while the Y field was located by Latitude. To correspond to the given base information, the coordinate system was chosen as WGS 84. The imported data was then transformed to spatial feature using *XY Table to Point*. The outcome was a point feature layer of the entrance and exit of tunnel galleries.

The road network layer was imported into the project to provide contextual information. Various shapefiles, related to the transportation network were loaded into the project and the coordinate system of each layer of data was checked to be compatible with the project. Incorporation of layers that originated from different coordinate systems required re-projection where layers were provided from the Project Tool under toolbox in ArcGIS Pro.

Figure 8. Galleries locations in Italy and fitting to the transportation network

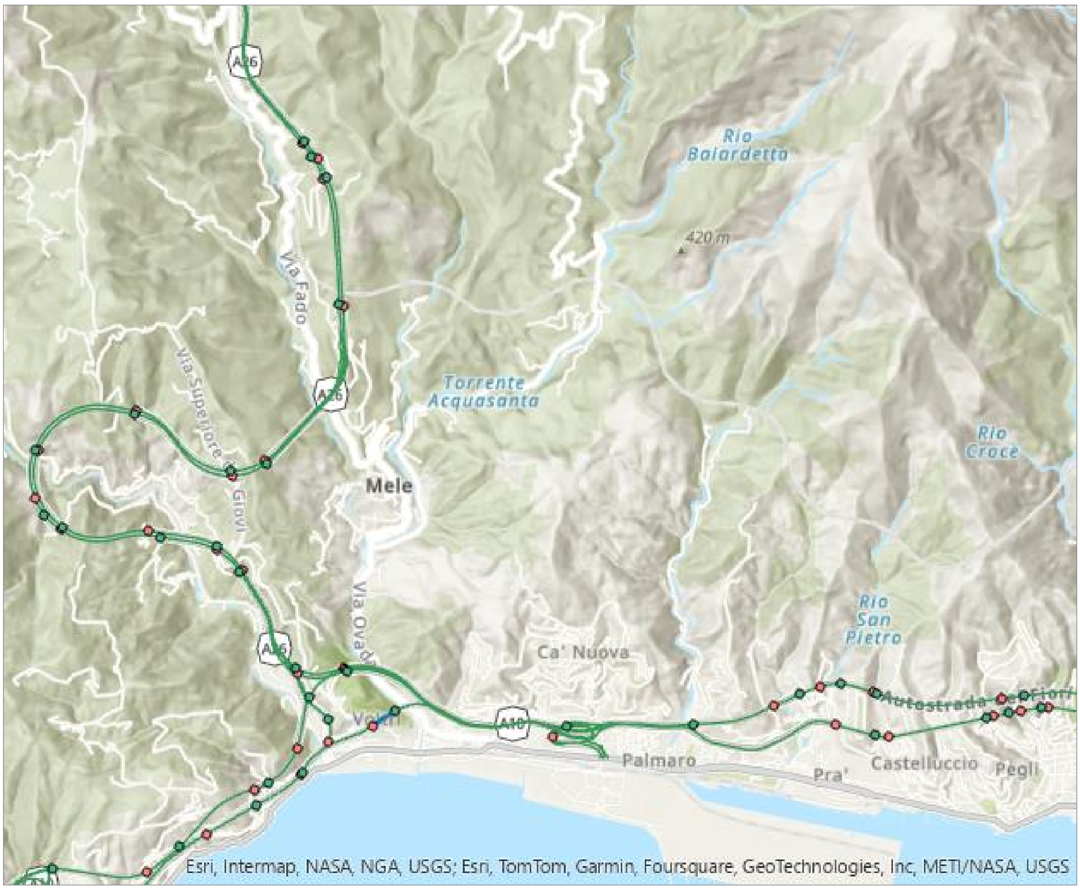


Figure 9. Galleries location close-up view (Liguria)

Gallery Starting Points.csv

Field: Add Calculate Selection: Select By Attributes

	Name	Longitude	Latitude	Type
1	Galleria-LOC. COZZUO...	12,288902	45,959714	Starting Point
2	Galleria di BASE DX VAR	11,191949	44,142297	Starting Point
3	Galleria di BASE SX VAR	11,238524	44,0736	Starting Point
4	Galleria SANTA LUCIA...	11,209234	43,953508	Starting Point
5	Galleria VAL di SAMBR...	11,200516	44,194512	Starting Point
6	Galleria VAL di SAMBR...	11,18467	44,226406	Starting Point
7	Galleria DELLE CAVE SX...	12,316238	46,129166	Starting Point
8	Galleria DELLE CAVE D...	12,324828	46,100686	Starting Point
9	Galleria MASSINO VIS...	8,537312	45,836931	Starting Point
10	Galleria MASSINO VIS...	8,535842	45,811873	Starting Point
11	Galleria SPARVO DX VAR	11,199209	44,188646	Starting Point
12	Galleria SPARVO SX VAR	11,196726	44,166548	Starting Point
13	Galleria POZZOLATICO...	11,226702	43,722179	Starting Point
14	Galleria GRIZZANA SX...	11,189809	44,258968	Starting Point
15	Galleria TARVISIO SX A...	13,595729	46,506357	Starting Point
16	Galleria TARVISIO DX A...	13,566964	46,507349	Starting Point
17	Galleria GRIZZANA DX...	11,189522	44,258901	Starting Point
18	Galleria ALTETA MANG...	11,218215	44,00961	Starting Point
19	Galleria MONTE MARI...	11,257789	44,370092	Starting Point

Figure 11. Galleries starting points attributes table

Gallery Ending Points.csv

Field: Add Calculate Selection: Select By Attributes

	Name	Longitude	Latitude	Type
1	Galleria-LOC. COZZUO...	12,289283	45,959898	Ending Point
2	Galleria di BASE DX VAR	11,238225	44,073406	Ending Point
3	Galleria di BASE SX VAR	11,192545	44,142424	Ending Point
4	Galleria SANTA LUCIA...	11,189868	43,894829	Ending Point
5	Galleria VAL di SAMBR...	11,184953	44,22649	Ending Point
6	Galleria VAL di SAMBR...	11,200188	44,194584	Ending Point
7	Galleria DELLE CAVE SX...	12,323742	46,095604	Ending Point
8	Galleria DELLE CAVE D...	12,316679	46,128615	Ending Point
9	Galleria MASSINO VIS...	8,535516	45,811915	Ending Point
10	Galleria MASSINO VIS...	8,537689	45,836638	Ending Point
11	Galleria SPARVO DX VAR	11,196209	44,166435	Ending Point
12	Galleria SPARVO SX VAR	11,199635	44,188574	Ending Point
13	Galleria POZZOLATICO...	11,25183	43,726727	Ending Point
14	Galleria GRIZZANA SX...	11,187611	44,239674	Ending Point
15	Galleria TARVISIO SX A...	13,566622	46,50753	Ending Point
16	Galleria TARVISIO DX A...	13,595485	46,506178	Ending Point
17	Galleria GRIZZANA DX...	11,187396	44,239802	Ending Point
18	Galleria ALTETA MANG...	11,210954	43,98995	Ending Point
19	Galleria MONTE MARI...	11,259866	44,390183	Ending Point

Figure 10. Galleries ending points attributes table

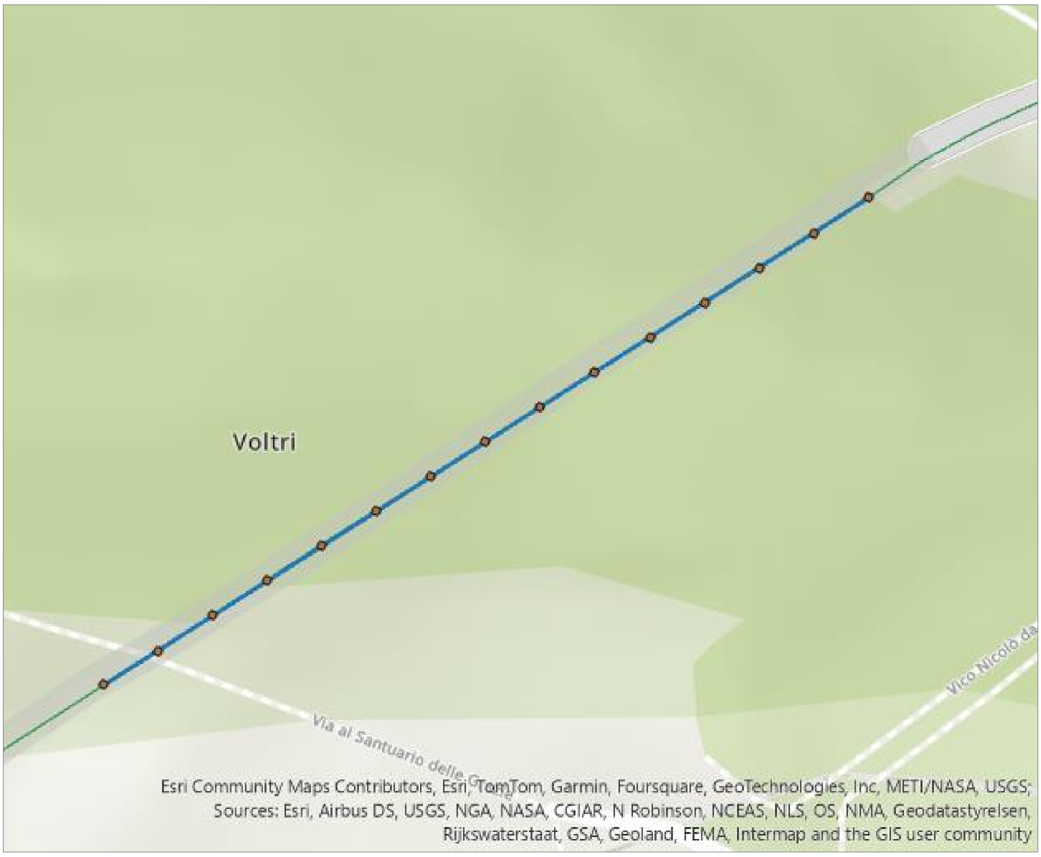


Figure 12. Tunnel section divided to equal distances as a preliminary testing of ideas

5.3. Interoperability: ArcGIS Pro and IoT

An occasional tunnel portion which is illustrated in **Figure 7** was chosen to test various ideas regarding the progress of the project. This tunnel, located in Liguria, Italy, was chosen for its simplicity and its linearity can be seen in the provided screenshot. It was then divided to equal distances, resulting in 15 points. For this proposal, there isn't provided a sensor placement, considering how it depends on a combined study of various parameters such as: geographic location, hydrogeological conditions, structural conditions, functionality and use, measured units, selected supplier, etc. Nevertheless, the 15 locations are hypothetically considered as the points in the tunnel where sensors are placed to monitor the changes in 4 parameters: temperature, humidity, vibrations and CO levels.

To be able to proceed with whatever proposal, at this stage was necessary to find the coordinates of these hypothetical points, generated along the selected tunnel portion. This was achieved following the sequence describe below and supported by screenshots.

Firstly, in the attributes table of the specific layer the Longitude and Latitude fields were added.

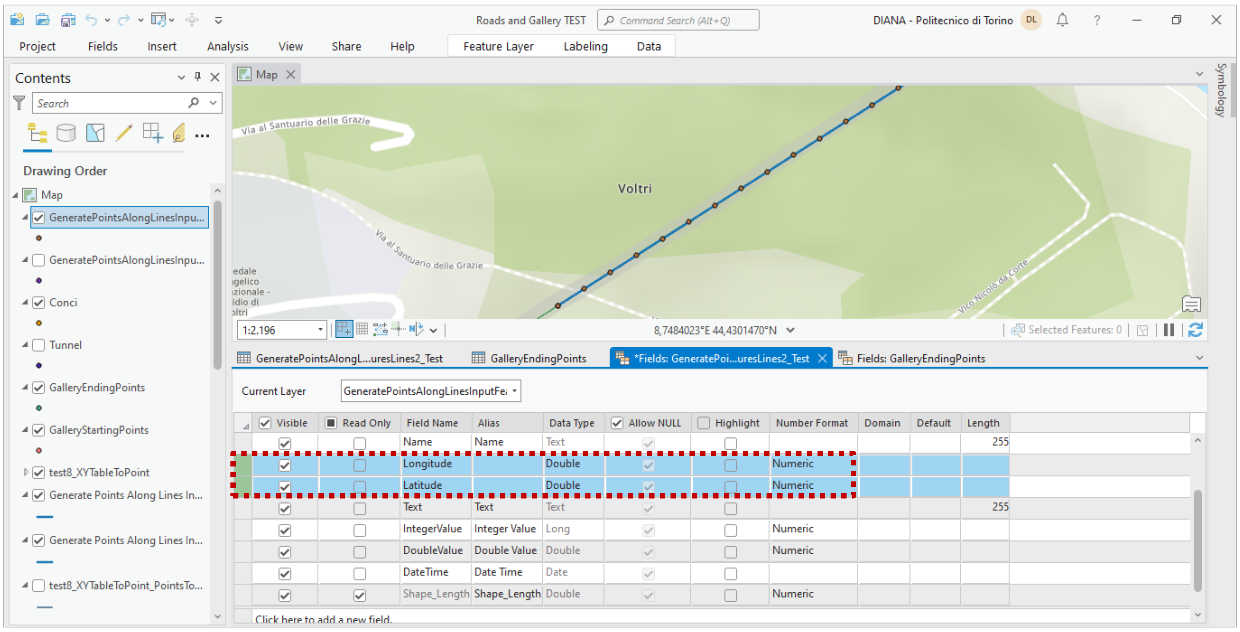


Figure 13. Layer editing

Then, *Analysis > Tools > Calculate geometry attributes*

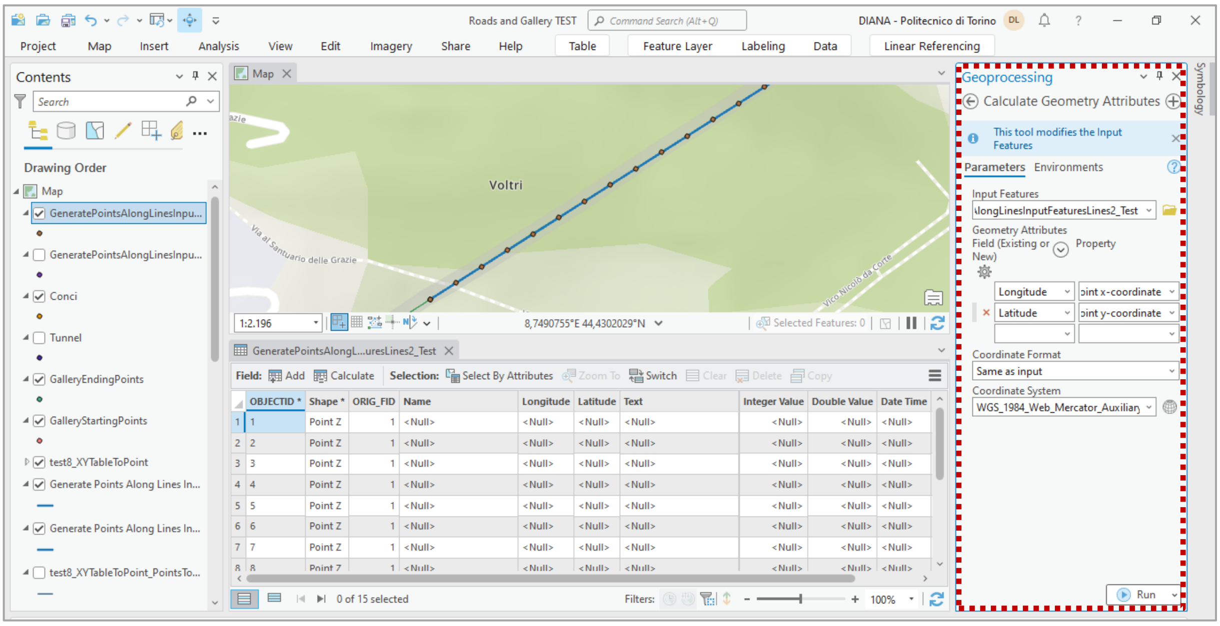
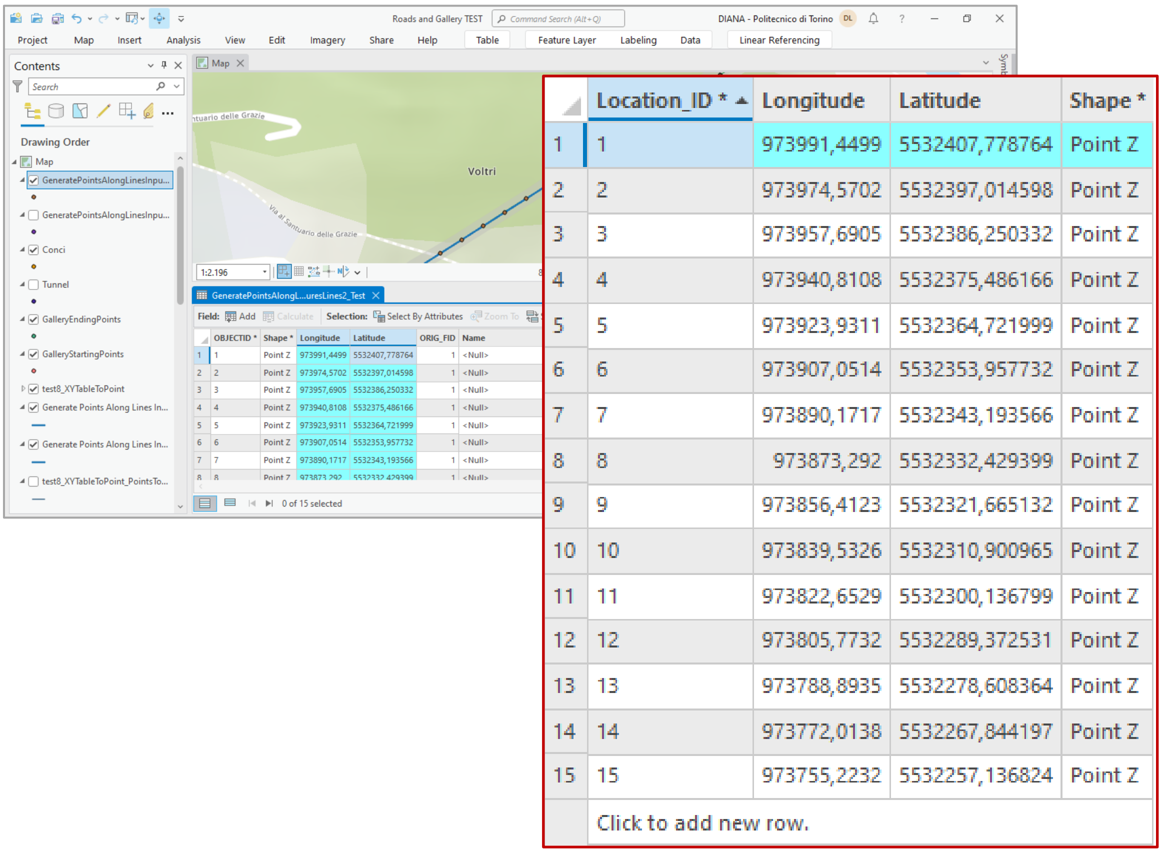


Figure 14. Coordinate calculation of the selected locations

As it can be seen, the x and y coordinates for each location are now calculated and added in the attributes table.



	Location_ID *	Longitude	Latitude	Shape *
1	1	973991,4499	5532407,778764	Point Z
2	2	973974,5702	5532397,014598	Point Z
3	3	973957,6905	5532386,250332	Point Z
4	4	973940,8108	5532375,486166	Point Z
5	5	973923,9311	5532364,721999	Point Z
6	6	973907,0514	5532353,957732	Point Z
7	7	973890,1717	5532343,193566	Point Z
8	8	973873,292	5532332,429399	Point Z
9	9	973856,4123	5532321,665132	Point Z
10	10	973839,5326	5532310,900965	Point Z
11	11	973822,6529	5532300,136799	Point Z
12	12	973805,7732	5532289,372531	Point Z
13	13	973788,8935	5532278,608364	Point Z
14	14	973772,0138	5532267,844197	Point Z
15	15	973755,2232	5532257,136824	Point Z
	Click to add new row.			

Figure 15. Attributes table close up

Many options were explored for the development of the idea and the original one was writing a Python script to generate a .csv file with measurements for 15 locations, each 10 and 5 seconds, for 10 minutes, for the 4 selected parameters. It was successfully achieved and the data could be visualized the envisioned way. Nevertheless, after careful consideration the option of writing a Python script which generates real-time data each 5 seconds was seen as best fit. To be able to then connect the script to the real points, the environment in ArcGIS Pro had to first be prepared.

An official shapefile was chosen and a feature class was created as illustrated below.

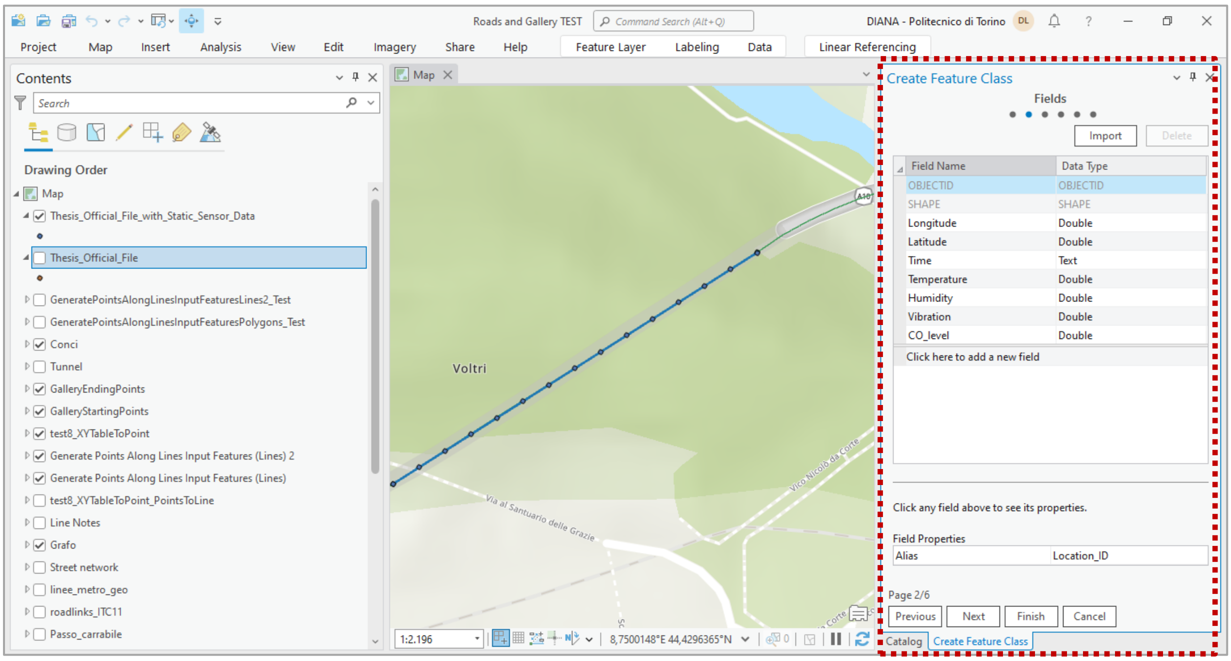


Figure 16. Procedure illustration

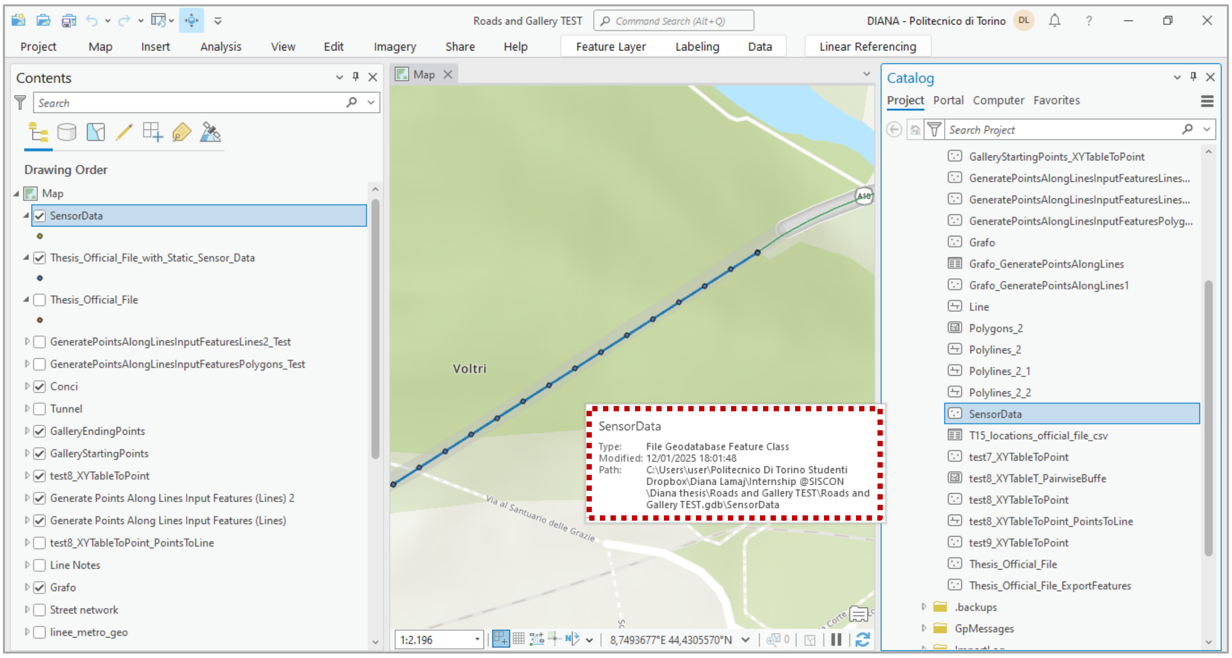


Figure 17. Newly created feature class

This new file was populated with data. Longitude and latitude were taken from the official shapefile, using the *Add Join* function.

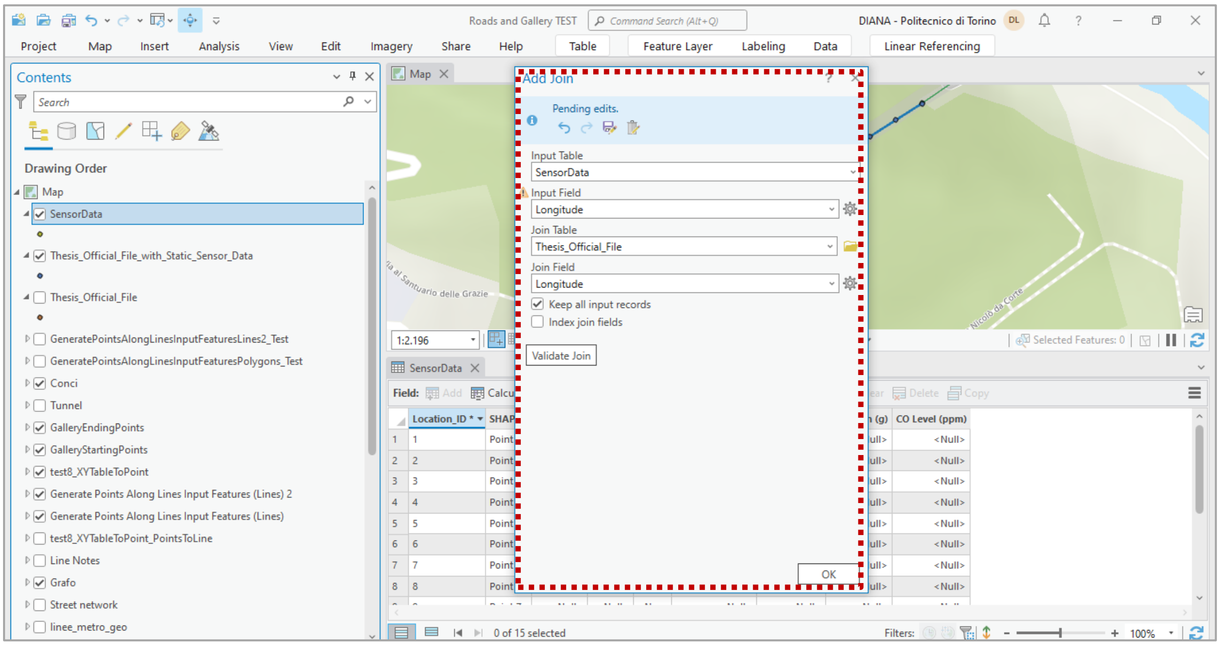


Figure 18. Add Join execution

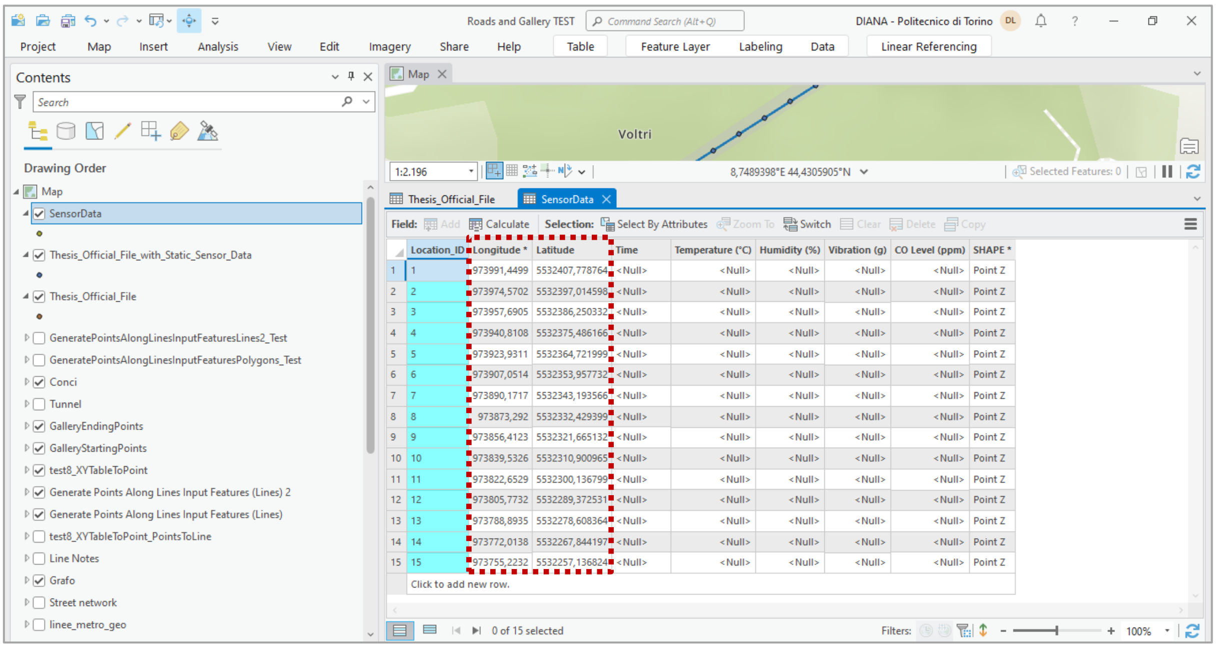


Figure 19. Populated attributes table

The data is exported and a new shapefile is created by following the sequence *Data > Export Features*.

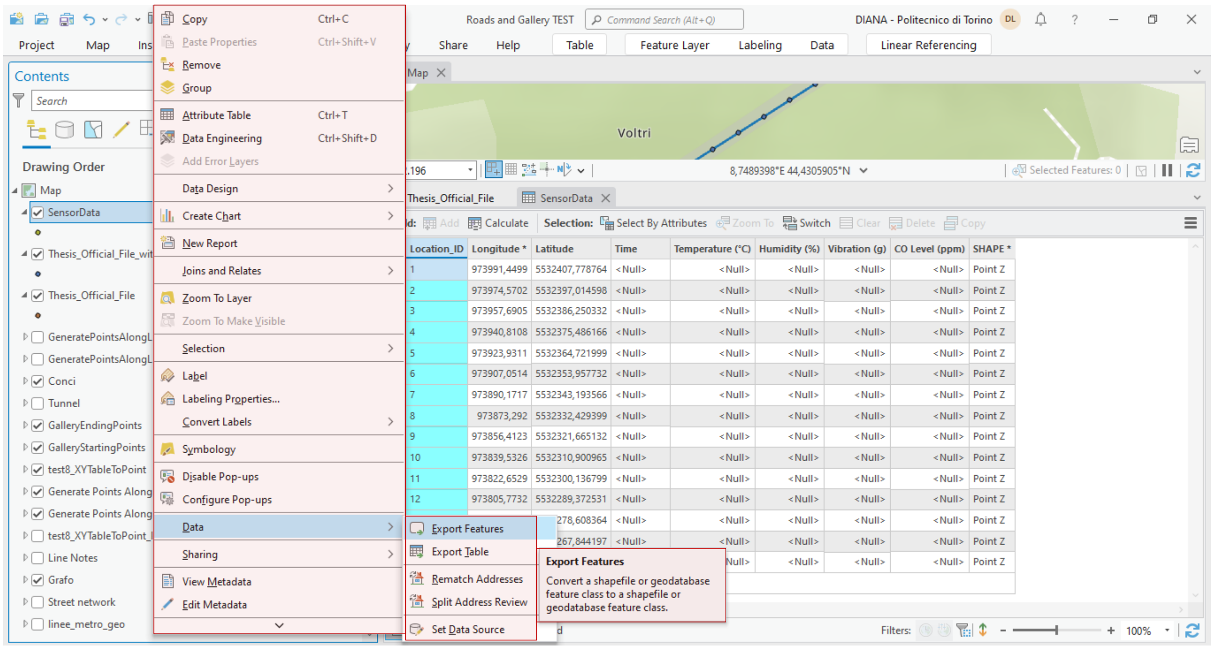


Figure 20. Sequence illustration

The shapefile has come at a state where it can be connected to the Python script to receive live data. The script is added below and comments can be found at every section of it, for better understanding

```
import pandas as pd # The libraries fundamental to achieve the goal
import numpy as np
import time
import arcpy

# Simulation parameters chosen for this project
update_interval_seconds = 5  # This line aims to show the time in which is
updated the feature class
locations = 15 # The locations based on the shapefile are 15
parameters = {
    "Temperature (°C)": (20, 5), # The data is generated in an indicative
way, around a mean and standard deviation, to mimic real sensor ones
    "Humidity (%)": (60, 10),
    "Vibration (g)": (0.05, 0.01),
    "CO Level (ppm)": (10, 2)
}

# File paths described below
gdb_path = r"C:\Users\user\Politecnico Di Torino Studenti Dropbox\Diana
Lamaj\Internship @SISCON\Diana thesis\Roads and Gallery TEST\Roads and
Gallery TEST.gdb"  # The path of the geodatabase being used
feature_class_name = "SensorData_Official_File"  # The feature class which
was just created
feature_class_path = f"{gdb_path}\\{feature_class_name}"
```

```
# Function to generate sensor data
def generate_sensor_data():
    """Generate random sensor data for all locations."""
    data = []
    current_time = time.strftime("%H:%M:%S", time.localtime())
    for loc in range(1, locations + 1):
        entry = {"OBJECTID": loc, "Time": current_time} # Was checked to
match the real full names of the fields in the attributes table
        for param, (mean, stddev) in parameters.items():
            entry[param] = round(np.random.normal(mean, stddev), 2)
        data.append(entry)
    return pd.DataFrame(data)

# Function to update the feature class
def update_feature_class(data):
    """Update the feature class with new sensor data."""
    fields = ["OBJECTID", "Time", "Temperature", "Humidity", "Vibration",
"CO_level"]# Was checked to match the real full names of the fields in the
attributes table

    # Start editing session
    with arcpy.da.UpdateCursor(feature_class_path, fields) as cursor:
        for row in cursor:
            location_id = row[0]
            # Match the location ID in the feature class with the new data
            updated_row = data.loc[data["OBJECTID"] == location_id]
            if not updated_row.empty:
                row[1] = updated_row["Time"].values[0]
                row[2] = updated_row["Temperature (°C)"].values[0]
                row[3] = updated_row["Humidity (%)"].values[0]
                row[4] = updated_row["Vibration (g)"].values[0]
                row[5] = updated_row["CO Level (ppm)"].values[0]
                cursor.updateRow(row)

# Main loop
def main():
    """Continuously update the feature class with dynamic sensor data."""
    print(f"Starting dynamic updates for {feature_class_path}")
    while True:
        # Generate new data
        new_data = generate_sensor_data()

        # Update the feature class
        update_feature_class(new_data)

        print(f"Feature class updated at {time.strftime('%H:%M:%S')}")
        time.sleep(update_interval_seconds)

if __name__ == "__main__":
    main()
```

This code was ran into the Python console of ArcGIS Pro and it was fully functional, as illustrated in the figures below.

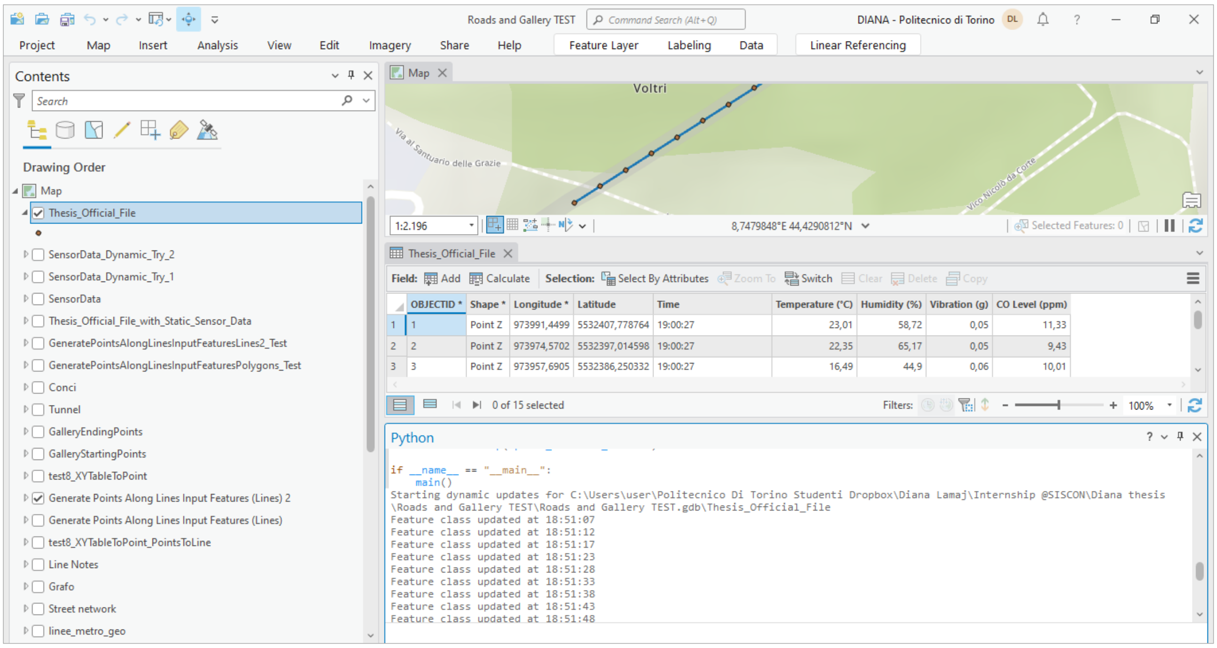


Figure 21. Data updates each 5 seconds while the script is running

While this code is running, everything stops and ArcGIS Pro can’t be used. Instead, a way of running the code externally is explored. Background processing for the Python script is enabled. This means that while the code runs, the software can be used without issue and the data can be accessed at any time. The procedure is described below.

The first step is creating a *Python Toolbox*. The sequence is *Insert > New Toolbox*.

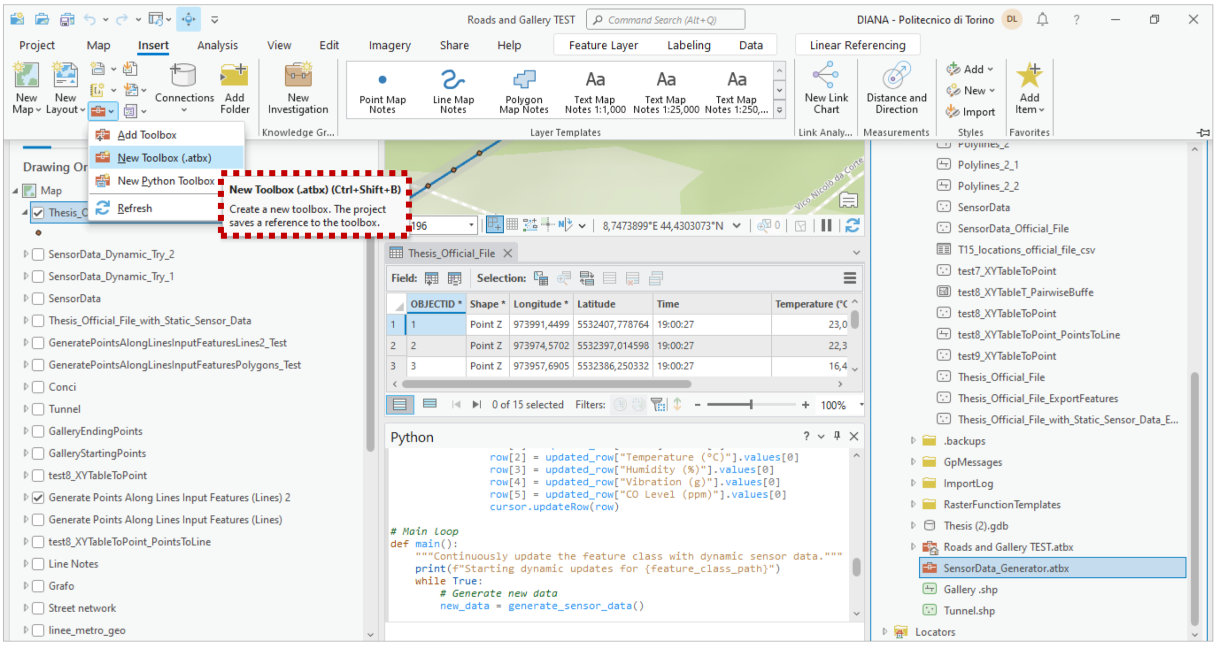


Figure 22. Python Toolbox creation

To the Toolbox, a Python script is added, following the steps *New > Script*

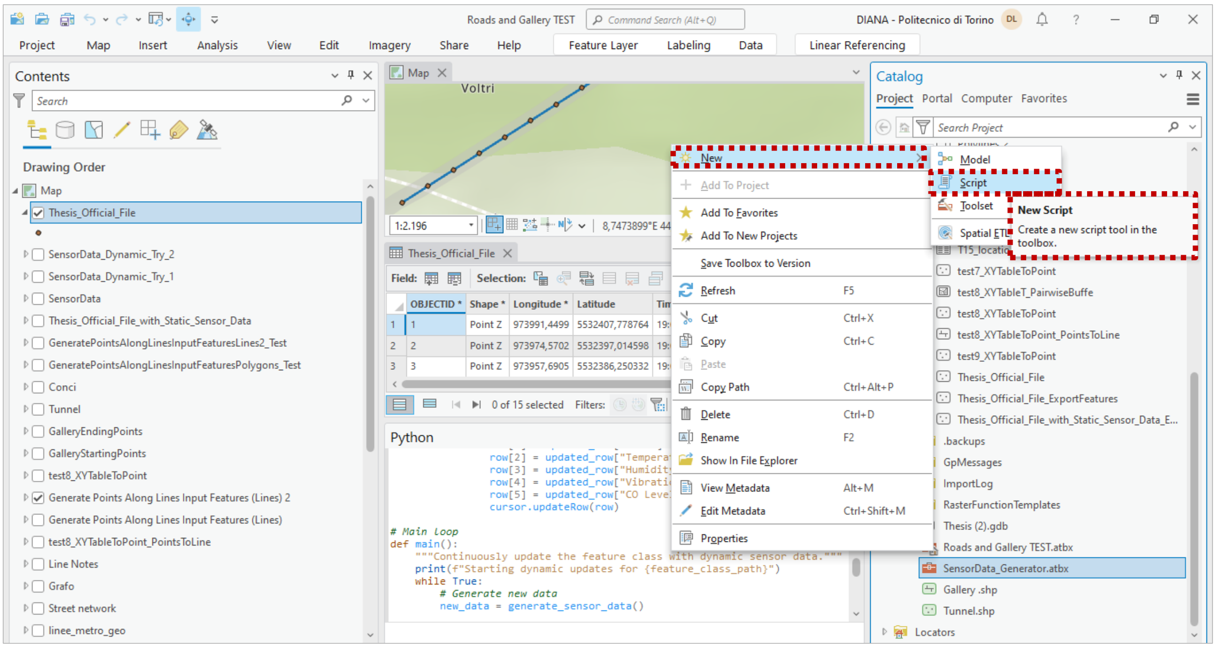


Figure 23. Script addition to the toolbox

The code is working without interrupting the functionalities of the software each location when clicked shows the measured parameters that have been last updated. However, the data has to be registered somewhere to ensure the completion of the idea, for these data to be used as a future data log to study the progress of each parameter in the tunnel and be able to monitor the state of the assets, as it develops with time.

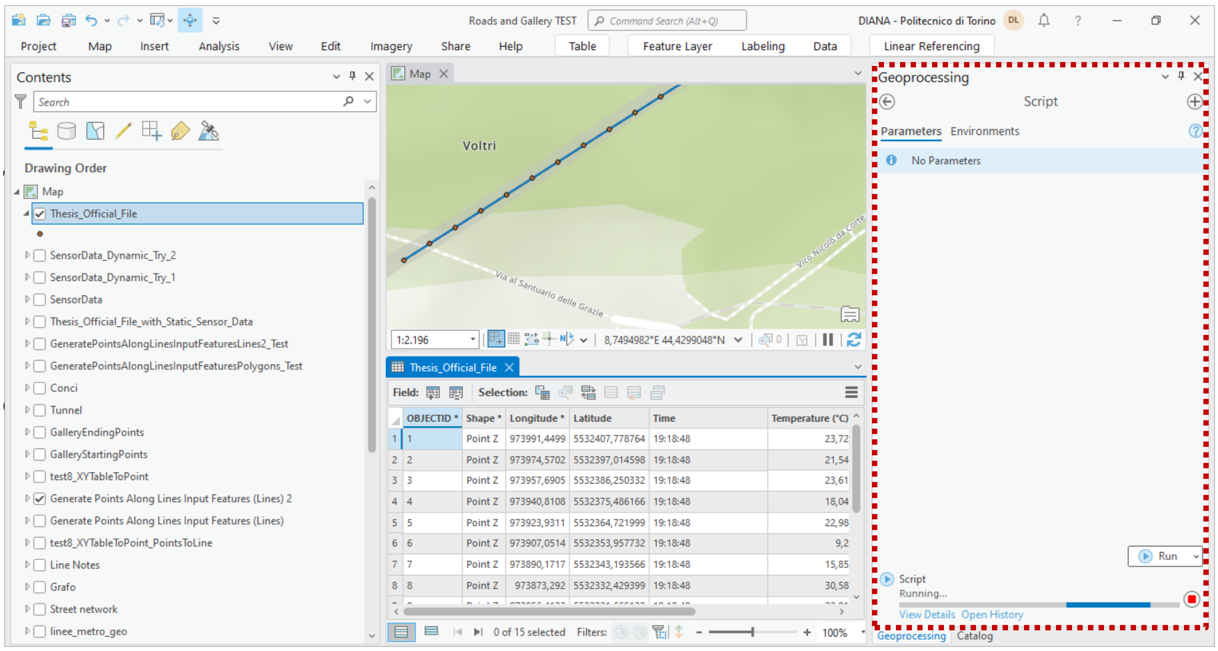


Figure 24. Script while running, results populating the attributes table

In the Geodatabase a new table is added. *Geodatabase > New > Table*

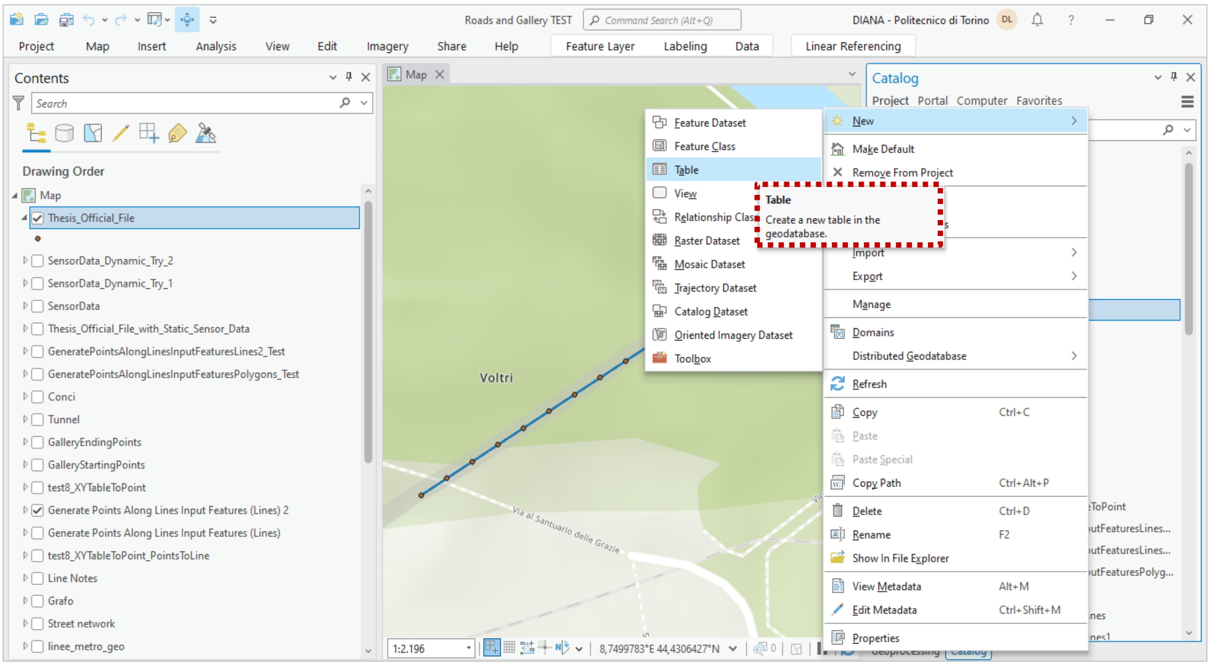


Figure 25. Table to store data creation

To the table are added all the fields which match the Python script and project requirements.

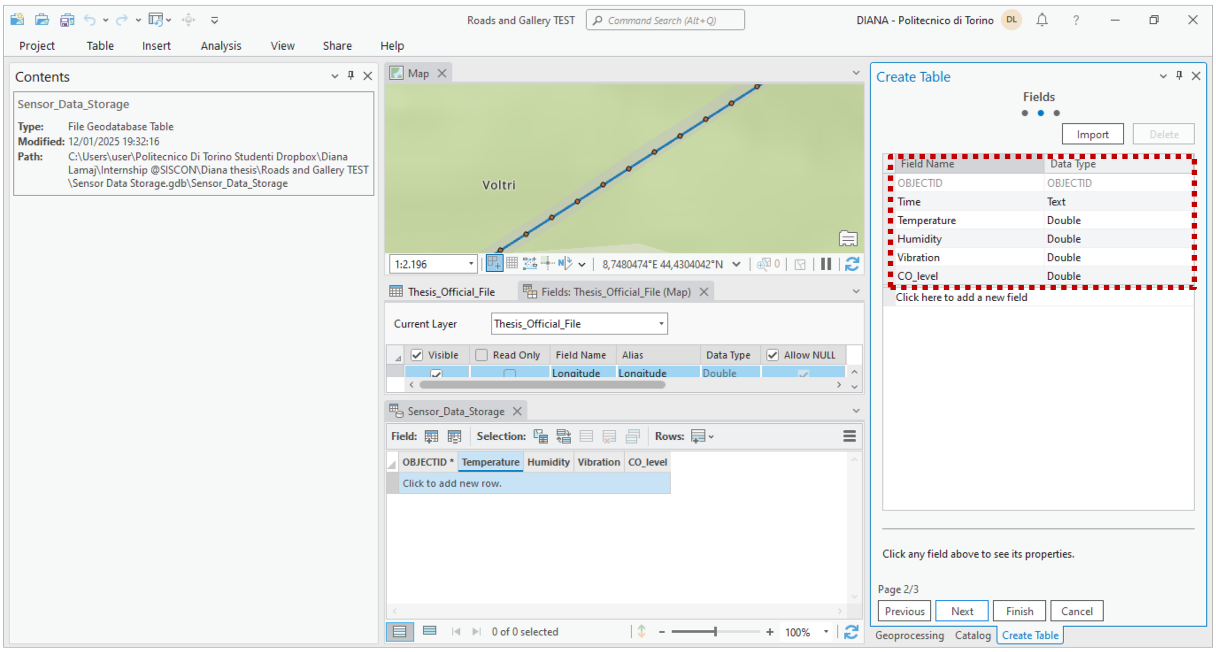


Figure 26. Table properties

The Script is adjusted into this new version which saves the data in the table also

```
import pandas as pd
import numpy as np
import time
import arcpy
# Simulation parameters
update_interval_seconds = 5  # How often the feature class shall be updated
locations = 15
parameters = {
    "Temperature (°C)": (20, 5),
    "Humidity (%)": (60, 10),
    "Vibration (g)": (0.05, 0.01),
    "CO Level (ppm)": (10, 2)
}
# File paths
gdb_path = r"C:\Users\user\Politecnico Di Torino Studenti Dropbox\Diana
Lamaj\Internship @SISCON\Diana thesis\Roads and Gallery TEST\Roads and
Gallery TEST.gdb"  # My geodatabase path
feature_class_name = "Thesis_Official_File"  # The feature class to update
dynamically
feature_class_path = f"{gdb_path}\\{feature_class_name}"
# Table path for saving historical data which will be used for future
studies, monitoring the health and asset state of the tunnel
table_name = "Sensor_Data_Storage_Table"  # This table exists in the
geodatabase, it's the one that was created just a little earlier
table_path = f"{gdb_path}\\{table_name}"
# Function to generate sensor data
def generate_sensor_data():
    """Generate random sensor data for all locations."""
    data = []
    current_time = time.strftime("%Y-%m-%d %H:%M:%S", time.localtime())
    for loc in range(1, locations + 1):
        entry = {"OBJECTID": loc, "Time": current_time}
        for param, (mean, stddev) in parameters.items():
            entry[param] = round(np.random.normal(mean, stddev), 2)
        data.append(entry)
    return pd.DataFrame(data)
# Function to update the feature class
def update_feature_class(data):
    """Update the feature class with new sensor data."""
    fields = ["OBJECTID", "Time", "Temperature", "Humidity", "Vibration",
"CO_level"]
    # Start editing session
    with arcpy.da.UpdateCursor(feature_class_path, fields) as cursor:
        for row in cursor:
            location_id = row[0]

            # Match the location ID in the feature class with the new data
            updated_row = data.loc[data["OBJECTID"] == location_id]
            if not updated_row.empty:
                row[1] = updated_row["Time"].values[0]
                row[2] = updated_row["Temperature (°C)"].values[0]
                row[3] = updated_row["Humidity (%)"].values[0]
                row[4] = updated_row["Vibration (g)"].values[0]
                row[5] = updated_row["CO Level (ppm)"].values[0]
                cursor.updateRow(row)
# Function to save data into the geodatabase table
def save_data_to_table(data):
    """Save the generated data to the historical table."""
    fields = ["OBJECTID", "Time", "Temperature", "Humidity", "Vibration",
```

```
"CO_level"]
    with arcpy.da.InsertCursor(table_path, fields) as cursor:
        for _, row in data.iterrows():
            cursor.insertRow([
                row["OBJECTID"],
                row["Time"],
                row["Temperature (°C)"],
                row["Humidity (%)"],
                row["Vibration (g)"],
                row["CO Level (ppm)"]
            ])
# Main loop
def main():
    """Continuously update the feature class with dynamic sensor data and
save history."""
    print(f"Starting dynamic updates for {feature_class_path}")
    while True:
        # Generate new data
        new_data = generate_sensor_data()
        # Update the feature class
        update_feature_class(new_data)
        # Save data to the historical table
        save_data_to_table(new_data)
        print(f"Feature class and historical table updated at
{time.strftime('%Y-%m-%d %H:%M:%S')}")
        time.sleep(update_interval_seconds)
if __name__ == "__main__":
    main()
```

Then, when the code runs again, the data uploads each 5 seconds into the shapefile and the details can be seen when clicking into the attributes table or a random point. The data is stored 15 by 15, for each location, in the dedicated table. The table can be refreshed, to add the newest received data. The process is illustrated in the screenshots below.

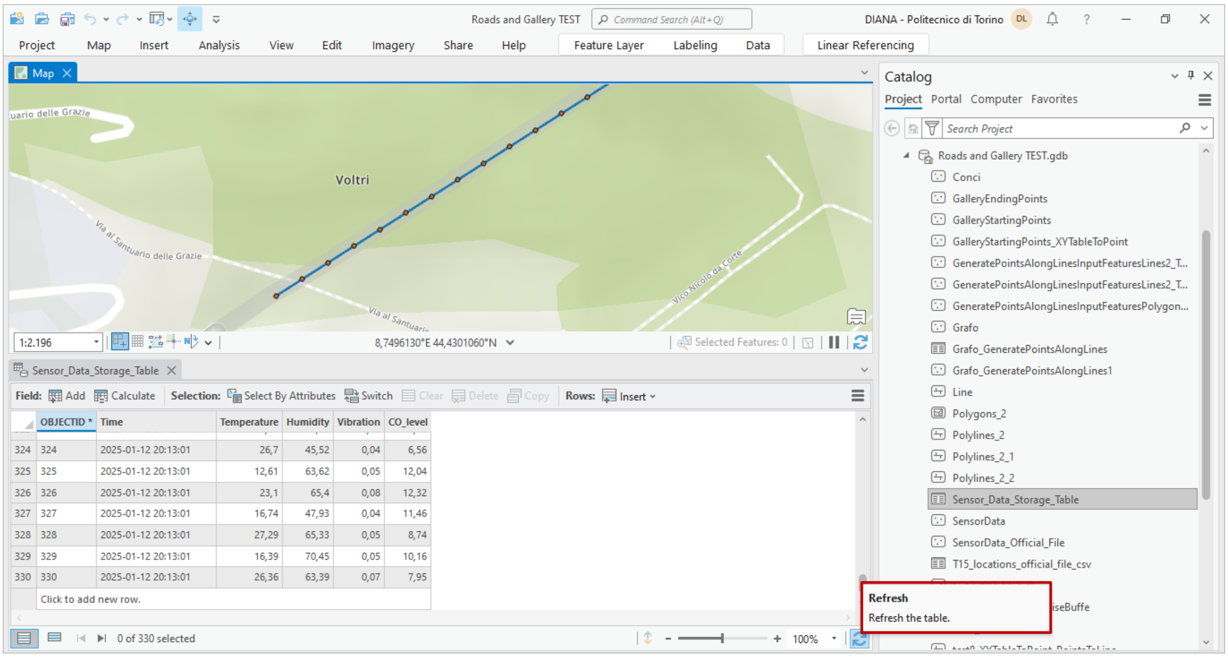


Figure 27. Table being fed real time data

The data is currently connected to the real locations, and time-enabled layers shall be used for dynamic visualization. The feature class which is in use is set as time-enabled. *Right-clicking the layer > Properties > Time.*

The timestamp field is chosen and time step is adjusted to 5 seconds, based on the sensor-transmitting data and they can be visualised changing in real-time, using the Time Slider.

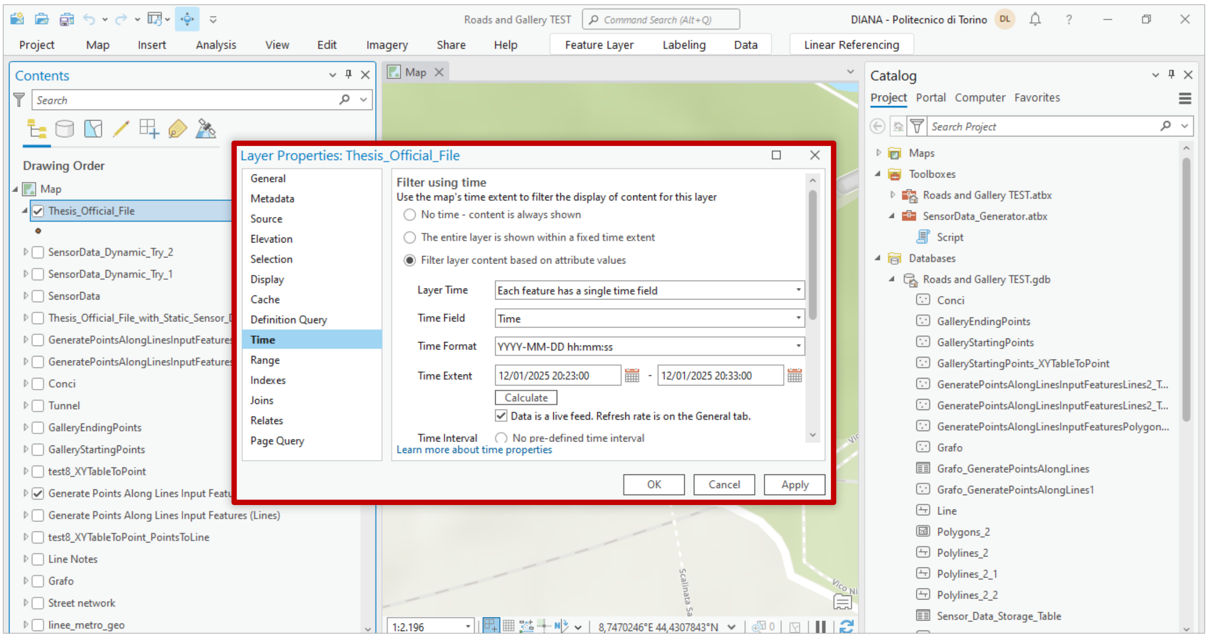


Figure 28. Time-enabling properties

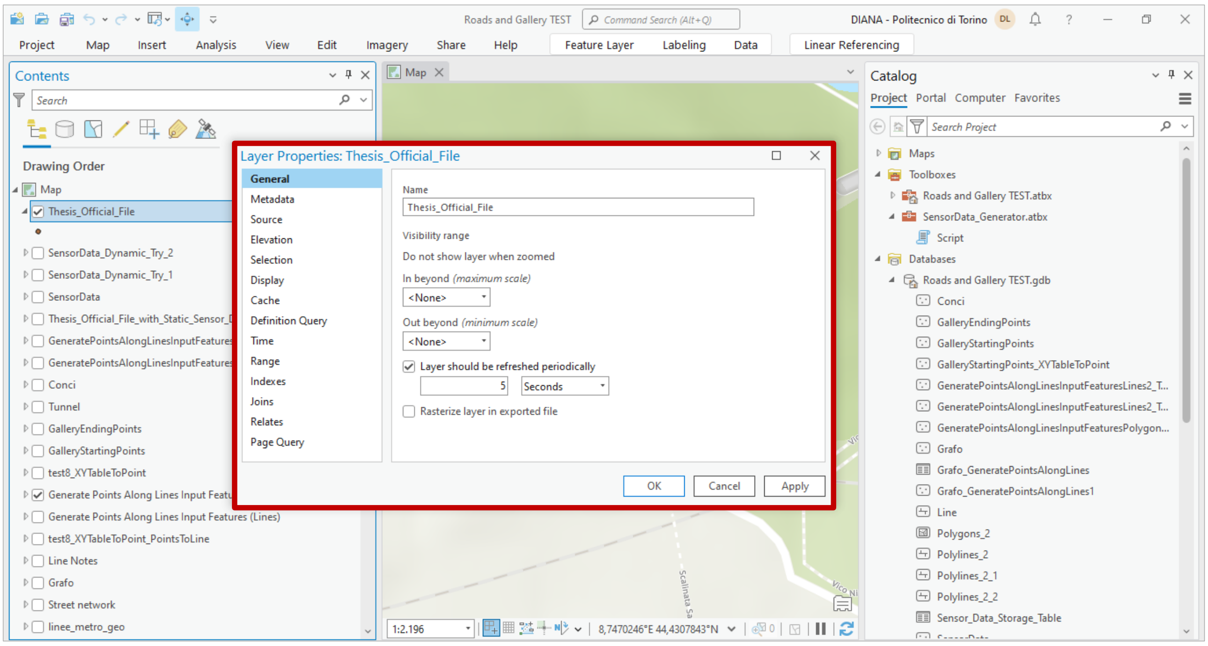


Figure 29. Layer refreshing period

The environment has been set to have a live-feed data, which means that the script can be run and the symbology can be adjusted in a preliminary way to test our project proposal for 1 parameter, in this case, the temperature. The idea is functioning and it is illustrated in the screenshot below.

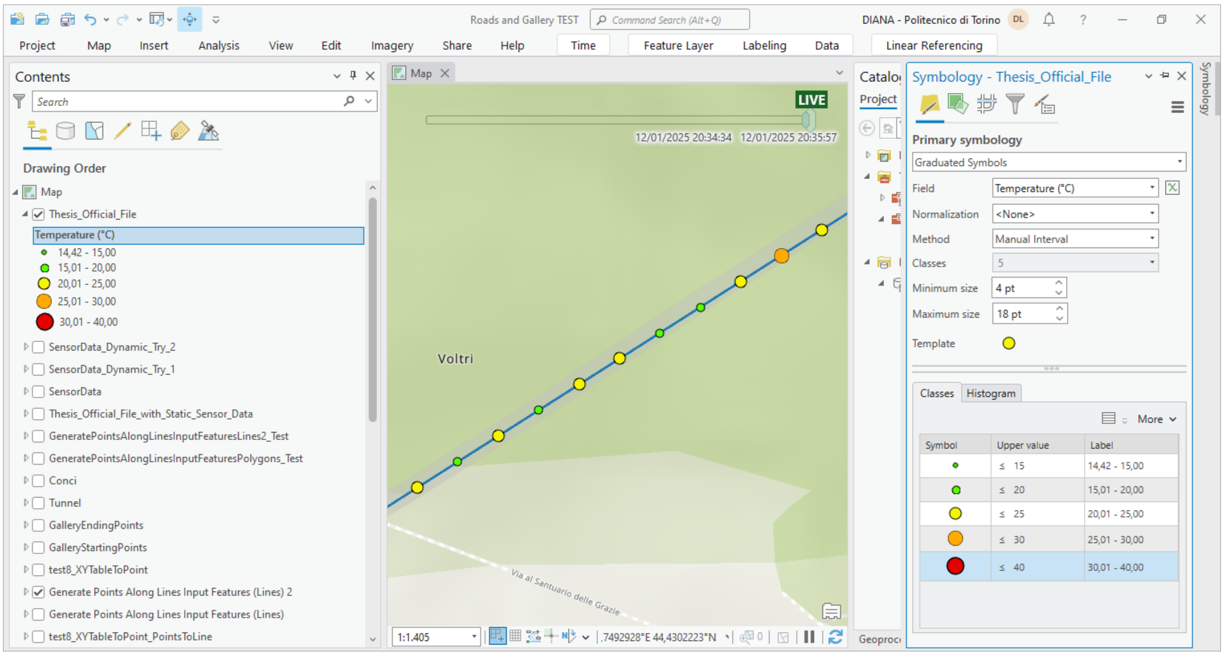


Figure 30. Temperature parameter real-time visualisation

The shapefile upon which the work is being developed is only one, so the symbology is removed from it. The original file with the original properties its copied and pasted 4 times, because the aim is to have 4 dedicated layers, 1 for each parameter. Copying the shapefile works without issues because:

1. Data source connection:

   When the shapefile in ArcGIS Pro is copied-pasted, the layer reference is being duplicating in the map project—not the actual data in the geodatabase. All these layers will still point to the same feature class in the geodatabase.
2. Real-Time updates:

   Since the Python script updates the geodatabase feature class directly, all map layers referencing that feature class will automatically reflect the changes in real-time.
3. Independent symbology

   Each duplicated layer can have unique symbology settings, even though they are fed by the same data source.

In the figure below can be seen the tested, preliminary legend for the division of the 4 parameters visualisation. It is subjected to change and updates, based on the obtained initial final product. The legend will normally depend on various factors which will affect the threshold values, such as the location of the tunnel, its dimensions, the regulations adopted by the country, the experts' evaluation, etc. For this proposal, considering the lack of presence of real data and access to local standards, the values are taken arbitrarily, to express the proposal for the audience.

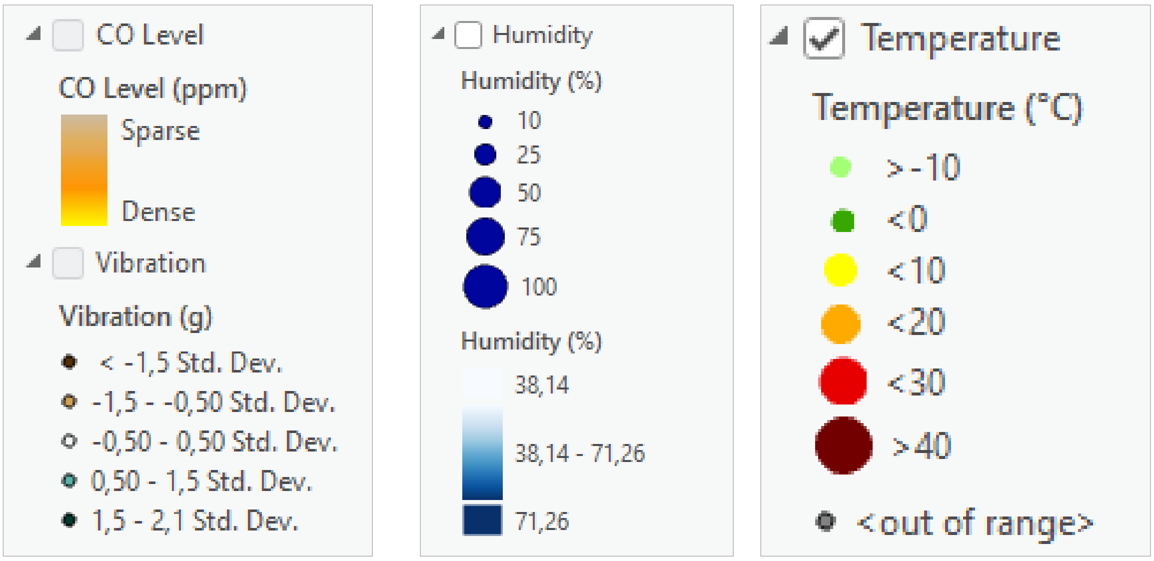


Figure 31. Parameters visualisation legend

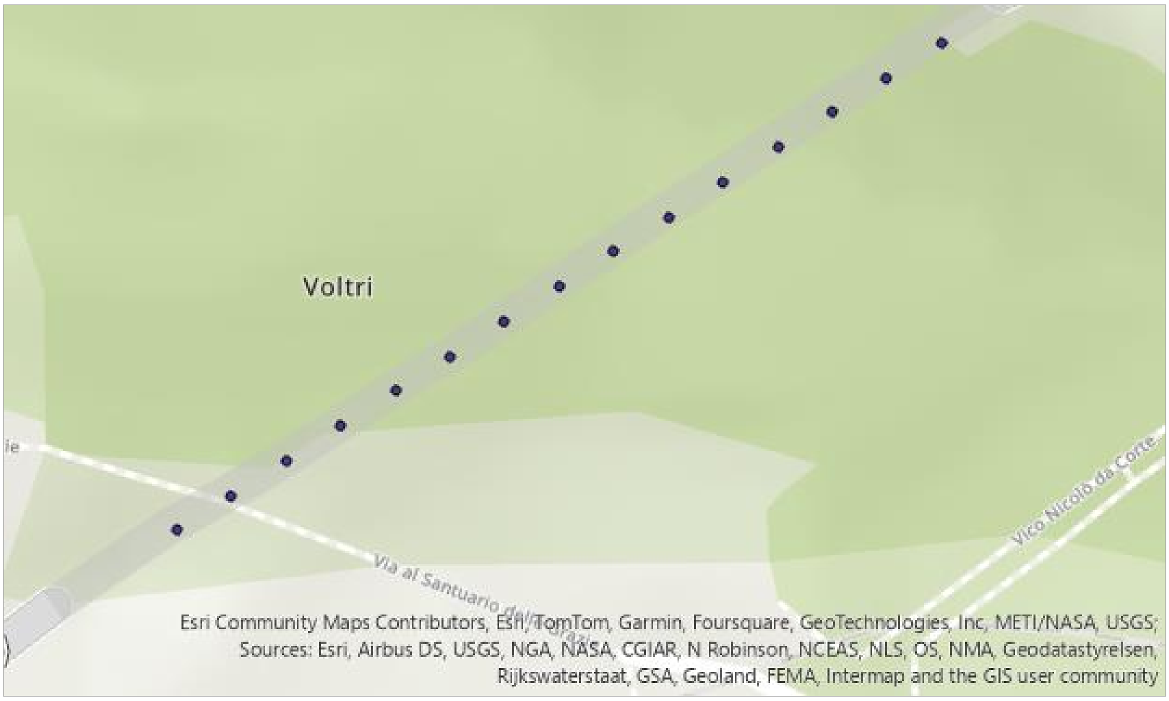


Figure 32. Selected locations while simulation is running

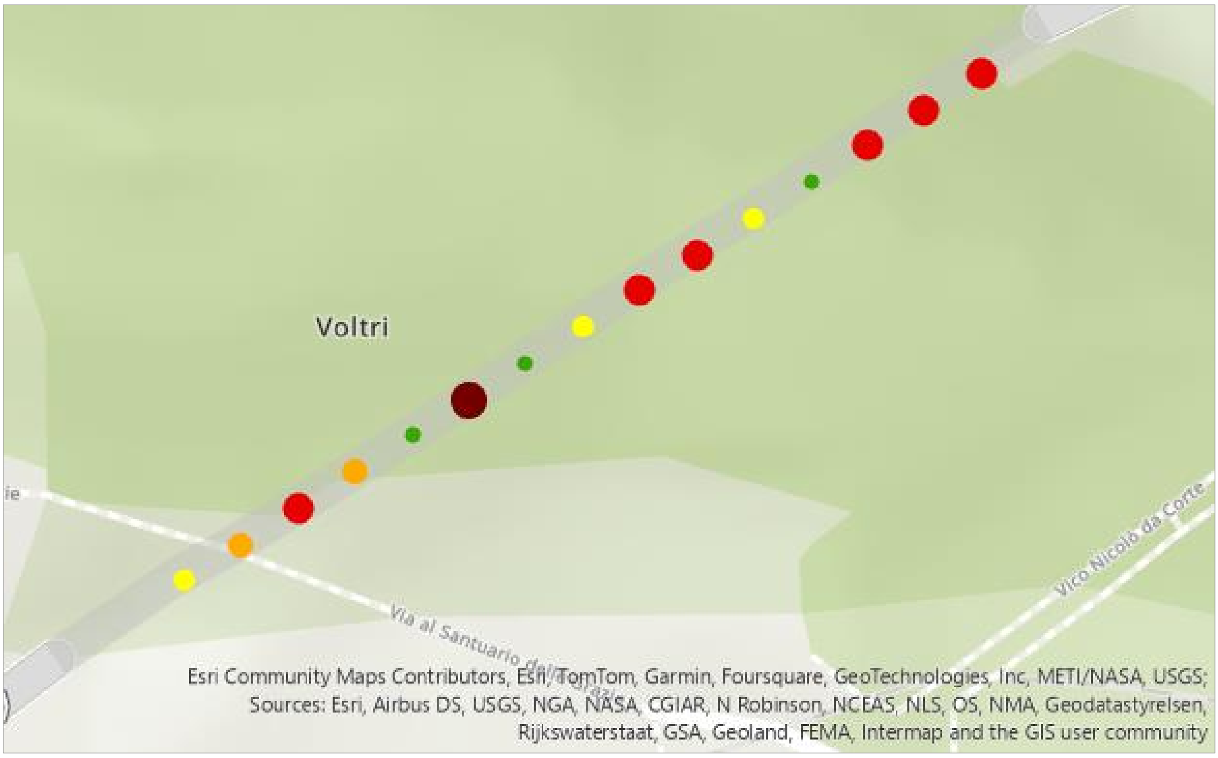


Figure 33. Temperature data visualisation while simulation is running

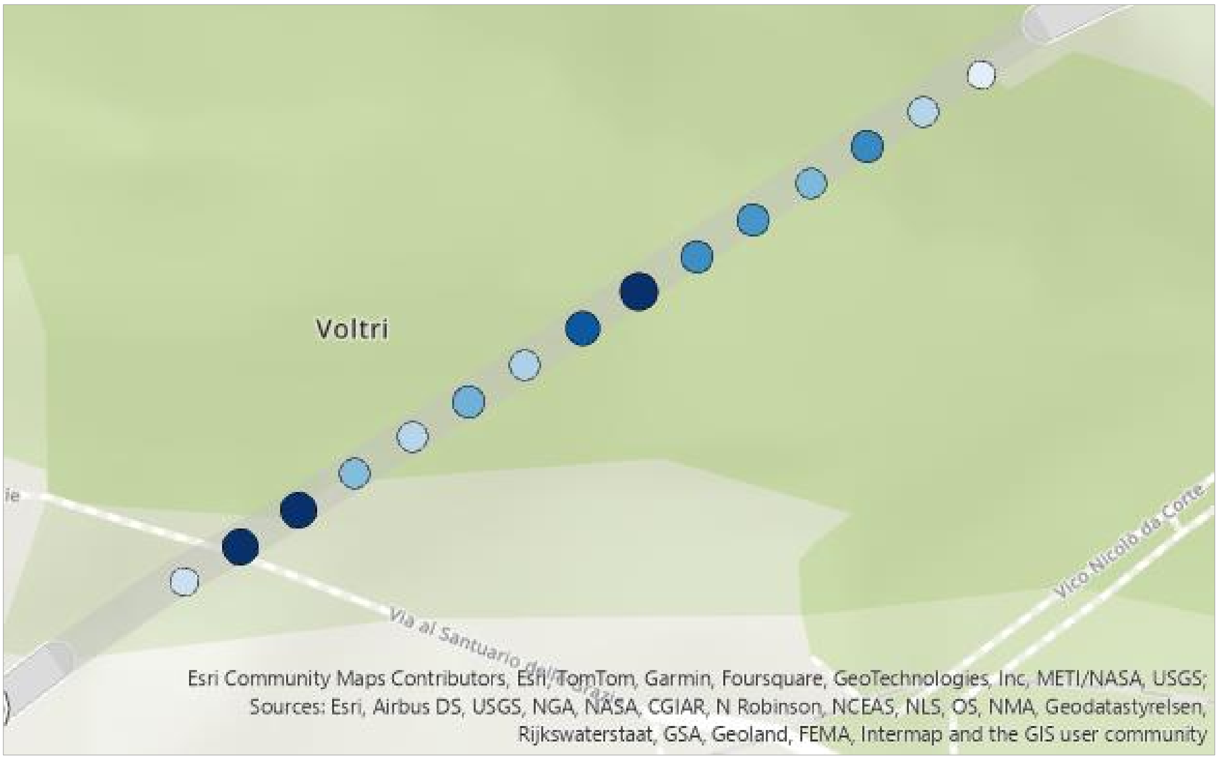


Figure 34. Humidity data visualisation while simulation is running

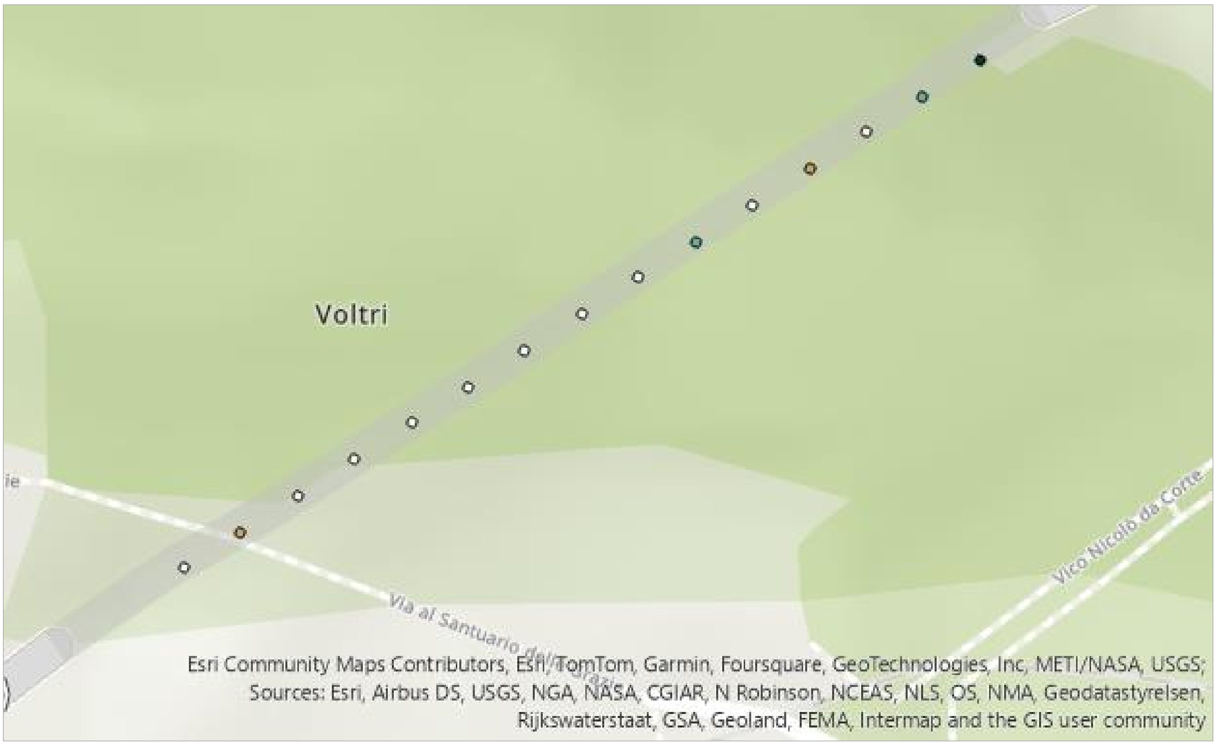


Figure 35. Vibration data visualisation while simulation is running

Figure 36. Hazardous gas data visualisation while simulation is running

5.3.1. Fire Simulation

To better visualise the concept behind this proposal, the code was refined to mimic data that could be retrieved in case of a fire in the tunnel. The new code aims to simulate the data in a realistic way for temperature, humidity, vibration and CO levels following a logic and progressive change based on proximity to the fire origin and spread over time. For this case, the fire was considered to start at the middle of the whole tunnel section, location 8, and the surrounding locations will be affected progressively as the fire spread. A feature to monitor the temperature in real time, a popup alert, was included in case of the temperature exceeding a threshold chosen just for the example. The popup to be displayed is: **`" WARNING! Rapid temperature increase detected at location {row['OBJECTID']}!"`**

The data shall change in the following way:

- **Temperature**: Decreases with distance from the fire and increases with time.
- **Humidity**: Drops near the fire origin.
- **Vibration**: Slightly increases as fire spreads.
- **Carbon Monoxide**: Rises with proximity to the fire and over time.

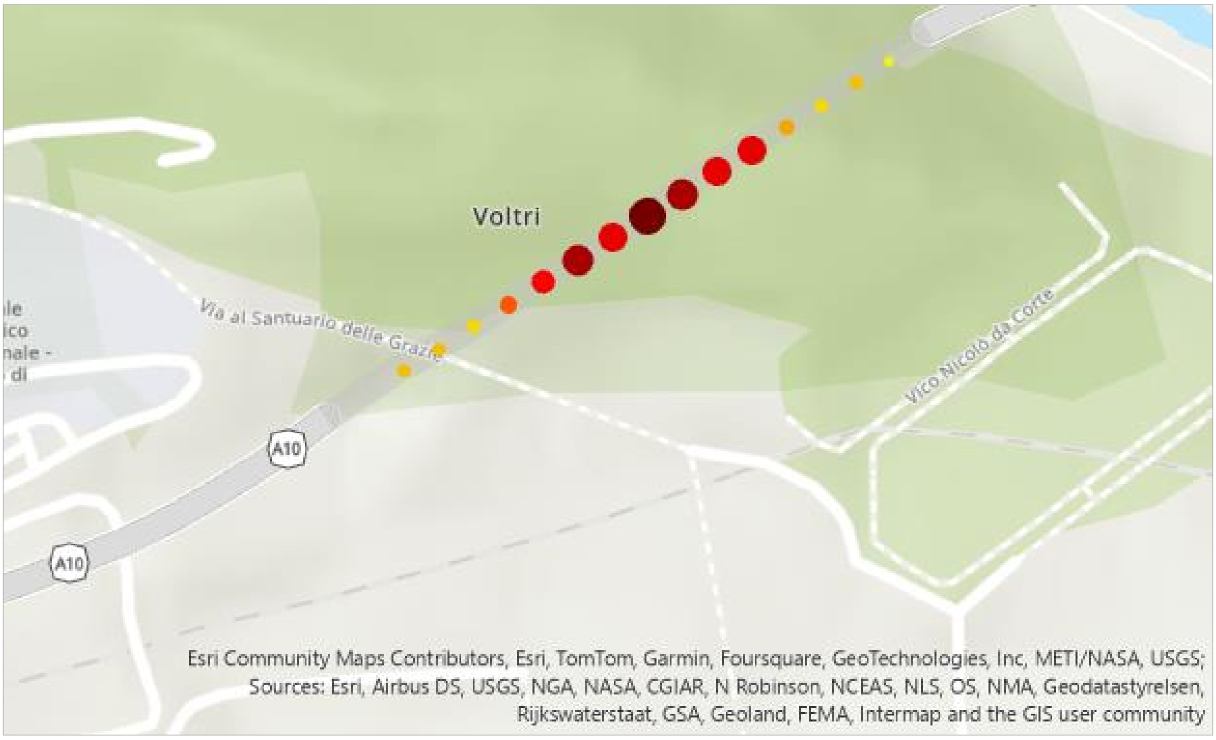


Figure 37. Fire Simulation - Temperature Monitoring

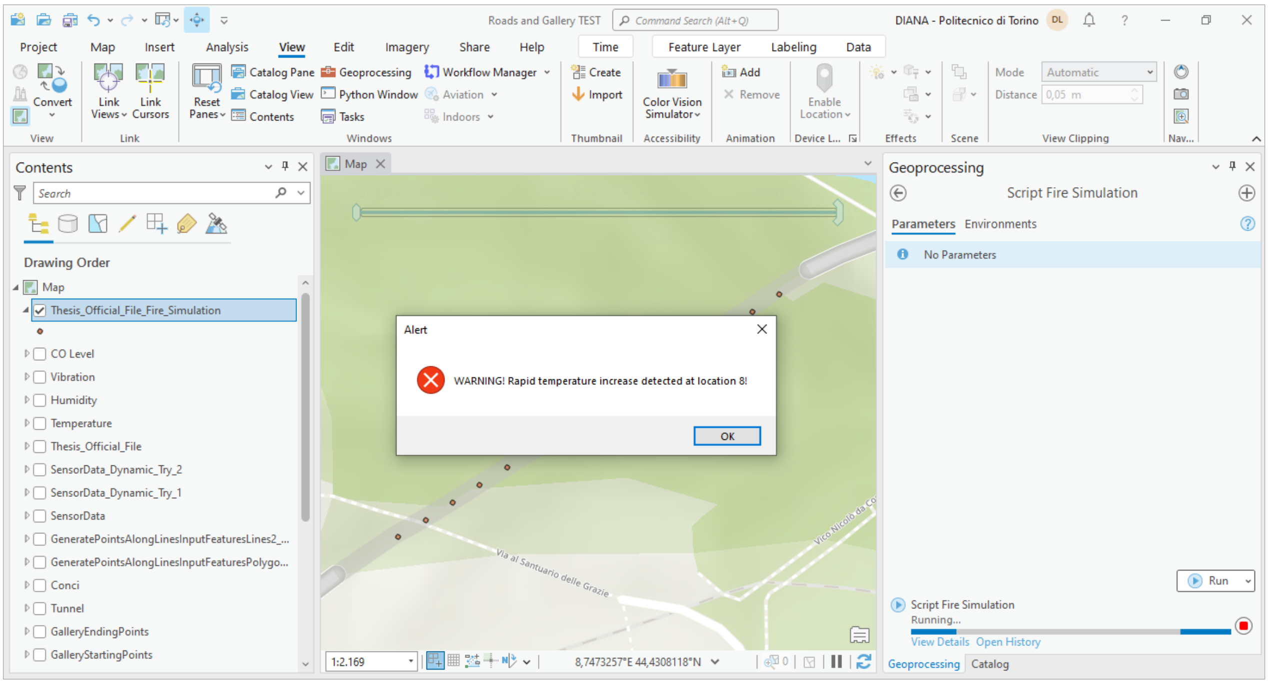


Figure 38. Warning Popup in case of suspicious parameter variation – Temperature

The script written and run for this purpose is based on the script used previously, with a few changes to adopt the requests and logical data in case of a fire. The script is the following:

```
import pandas as pd
import numpy as np
import time
import arcpy
import ctypes
# Simulation parameters
update_interval_seconds = 5  # Update interval in seconds
locations = 15
parameters = {
    "Temperature (°C)": (20, 5),
    "Humidity (%)": (60, 10),
    "Vibration (g)": (0.05, 0.01),
    "CO Level (ppm)": (10, 2)
}
# File paths
gdb_path = r"C:\Users\user\Politecnico Di Torino Studenti Dropbox\Diana
Lamaj\Internship @SISCON\Diana thesis\Roads and Gallery TEST\Roads and
Gallery TEST.gdb"
feature_class_name = "Thesis_Official_File_ExportFeatures1"
feature_class_path = f"{gdb_path}\\{feature_class_name}"
table_name = "Fire_Simulation_Data_Storage_Table"
table_path = f"{gdb_path}\\{table_name}"
fire_start = 8  # Fire starts at location 8
# Function to generate fire simulation sensor data
def generate_sensor_data():
    data = []
    current_time = time.strftime("%Y-%m-%d %H:%M:%S", time.localtime())
    for loc in range(1, locations + 1):
```

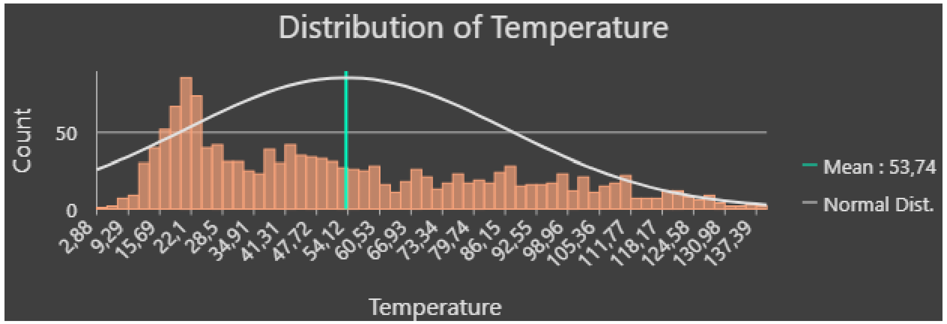
```
        entry = {"OBJECTID": loc, "Time": current_time}
        distance = abs(loc - fire_start)
        fire_temperature_increase = max(0, 80 - (distance * 15))
        entry["Temperature (°C)"] = round(fire_temperature_increase +
np.random.normal(40, 10), 2)
        entry["Humidity (%)"] = round(60 - (distance * 10) +
np.random.normal(0, 15), 2)
        entry["CO Level (ppm)"] = round(10 + (distance * 4) +
np.random.normal(0, 5), 2)
        entry["Vibration (g)"] = round(np.random.normal(0.1, 0.02), 2)
        data.append(entry)
    return pd.DataFrame(data)
# Function to update the feature class
def update_feature_class(data):
    fields = ["OBJECTID", "Time", "Temperature", "Humidity", "Vibration",
"CO_Level"]
    with arcpy.da.UpdateCursor(feature_class_path, fields) as cursor:
        for row in cursor:
            location_id = row[0]
            updated_row = data.loc[data["OBJECTID"] == location_id]
            if not updated_row.empty:
                row[1] = updated_row["Time"].values[0]
                row[2] = updated_row["Temperature (°C)"].values[0]
                row[3] = updated_row["Humidity (%)"].values[0]
                row[4] = updated_row["Vibration (g)"].values[0]
                row[5] = updated_row["CO Level (ppm)"].values[0]
                cursor.updateRow(row)
# Function to save data to the geodatabase table
def save_data_to_table(data):
    fields = ["OBJECTID", "Time", "Temperature", "Humidity", "Vibration",
"CO_Level"]
    with arcpy.da.InsertCursor(table_path, fields) as cursor:
        for _, row in data.iterrows():
            cursor.insertRow([
                row["OBJECTID"],
                row["Time"],
                row["Temperature (°C)"],
                row["Humidity (%)"],
                row["Vibration (g)"],
                row["CO Level (ppm)"]
            ])
# Function to trigger a system popup alert
def alert_popup(message):
    ctypes.windll.user32.MessageBoxW(0, message, "WARNING", 0x10)
# Main loop
def main():
    print(f"Starting dynamic updates for {feature_class_path}")
    while True:
        new_data = generate_sensor_data()
        for _, row in new_data.iterrows():
            if row["Temperature (°C)"] > 100:
                alert_popup(f"WARNING! Rapid temperature increase detected
at location {row['OBJECTID']}!")
        update_feature_class(new_data)
        save_data_to_table(new_data)
        print(f"Feature class and historical table updated at
{time.strftime('%Y-%m-%d %H:%M:%S')}")
        time.sleep(update_interval_seconds)
if __name__ == "__main__":
    main(
```

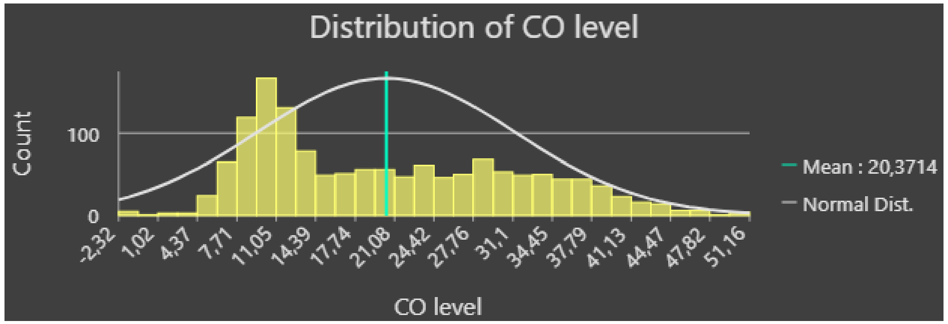
A snippet from the storage data table, showing the results of 3 consecutive simulations and some ArcGIS Pro statistics regarding the fire simulation data, temperature and CO level, are represented below.

Table 2. Fire simulation data snippet

OBJECT ID	Time	Temperature (°C)	Humidity (%)	Vibration (g)	CO level (ppm)
421 – 1	2025-01-27 17:54:22	13,14	55,35	0,04	9,37
422 – 2	2025-01-27 17:54:22	20,1	94,3	0,05	12,09
423 – 3	2025-01-27 17:54:22	21,89	70,39	0,06	10,97
424 – 4	2025-01-27 17:54:22	20,56	67,21	0,05	10,77
425 – 5	2025-01-27 17:54:22	22,27	54,4	0,04	13,64
426 – 6	2025-01-27 17:54:22	23,19	70,89	0,05	12,87
427 – 7	2025-01-27 17:54:22	20,88	55,03	0,03	6,82
428 – 8	2025-01-27 17:54:22	20,1	59,59	0,04	6,8
429 – 9	2025-01-27 17:54:22	27,75	63,66	0,05	10,08
430 – 10	2025-01-27 17:54:22	30,49	72,88	0,04	7,65
431 – 11	2025-01-27 17:54:22	16,76	66,32	0,04	4,91
432 – 12	2025-01-27 17:54:22	16,51	67,99	0,05	7,78
433 – 13	2025-01-27 17:54:22	21,97	58,55	0,06	10,23
434 – 14	2025-01-27 17:54:22	30,22	60,46	0,07	7,36
435 – 15	2025-01-27 17:54:22	8,9	50,07	0,05	12,31
436 – 1	2025-01-27 18:02:06	42,41	-5	0,16	40,19
437 – 2	2025-01-27 18:02:06	39,16	-14,71	0,09	34,51
438 – 3	2025-01-27 18:02:06	52,53	-10,76	0,11	29,57
439 – 4	2025-01-27 18:02:06	51,4	1,32	0,1	27,62
440 – 5	2025-01-27 18:02:06	70,8	21,67	0,08	21,56
441 – 6	2025-01-27 18:02:06	86,12	51,96	0,1	25,89
442 – 7	2025-01-27 18:02:06	97,57	62,13	0,12	18,12
443 – 8	2025-01-27 18:02:06	123,7	66,65	0,1	8,4
444 – 9	2025-01-27 18:02:06	100,36	26,53	0,09	8,29

445 – 10	2025-01-27 18:02:06	80,4	27,48	0,14	16,96
446 – 11	2025-01-27 18:02:06	76,79	30,88	0,09	14,52
447 – 12	2025-01-27 18:02:06	48,03	14,28	0,06	23,65
448 – 13	2025-01-27 18:02:06	65,39	33,73	0,11	30,45
449 – 14	2025-01-27 18:02:06	34,18	15,02	0,11	24,19
450 – 15	2025-01-27 18:02:06	43,07	1,61	0,11	36,74
451 – 1	2025-01-27 18:02:12	54,29	6,98	0,1	46,94
452 – 2	2025-01-27 18:02:12	44,85	-2,33	0,1	27,99
453 – 3	2025-01-27 18:02:12	36,29	18,07	0,08	28,86
454 – 4	2025-01-27 18:02:12	57,03	24,57	0,09	29,03
455 – 5	2025-01-27 18:02:12	83,59	9,27	0,09	24,37
456 – 6	2025-01-27 18:02:12	83,62	32,27	0,1	24,24
457 – 7	2025-01-27 18:02:12	88,8	42,02	0,11	17,41
458 – 8	2025-01-27 18:02:12	118,41	63,25	0,07	9,28
459 – 9	2025-01-27 18:02:12	97,26	32,38	0,11	16,63
460 – 10	2025-01-27 18:02:12	69,97	43,06	0,09	20,61
461 – 11	2025-01-27 18:02:12	97,15	13,77	0,08	23,55
462 – 12	2025-01-27 18:02:12	45,64	23,77	0,1	28,14
463 – 13	2025-01-27 18:02:12	38,27	24,04	0,09	27,85
464 – 14	2025-01-27 18:02:12	66,4	1,76	0,1	29,69
465 – 15	2025-01-27 18:02:12	26,4	7,14	0,1	27,64





5.4. Dashboard creation

With the GIS is all set the next step is preparing the dashboard.

A. Project data sharing in ArcGIS Online.

Feature Class in ArcGIS Pro, Share > Web Layer > Publish Web Layer.

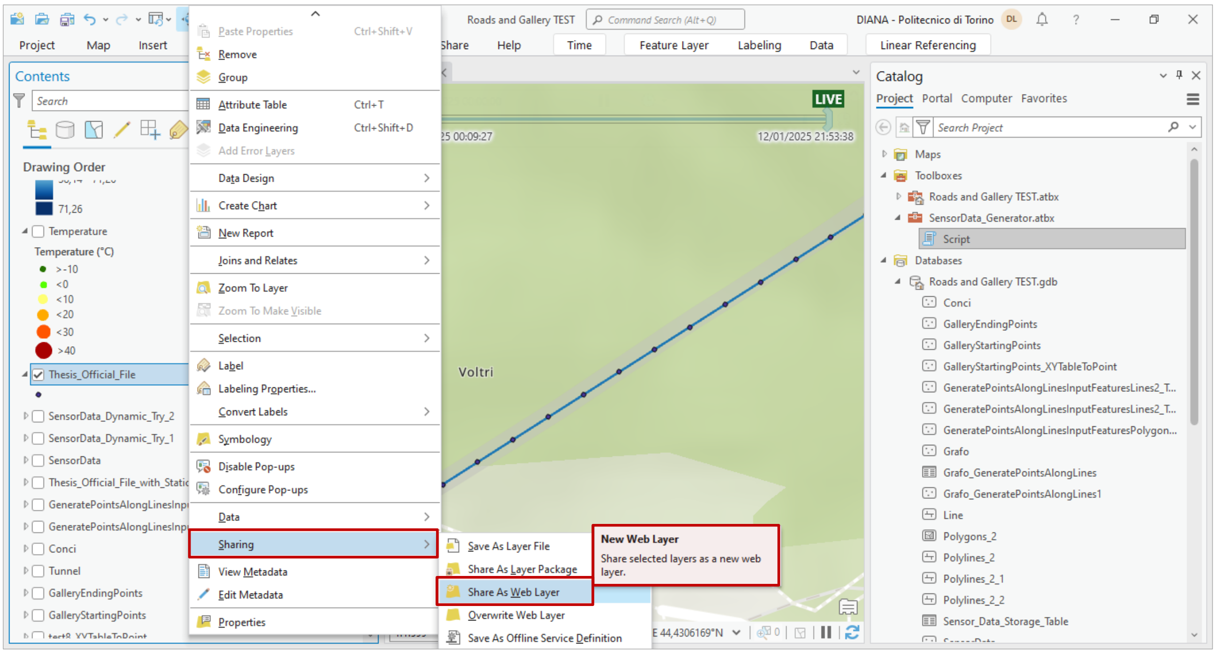


Figure 39. Publishing of the Web Layer

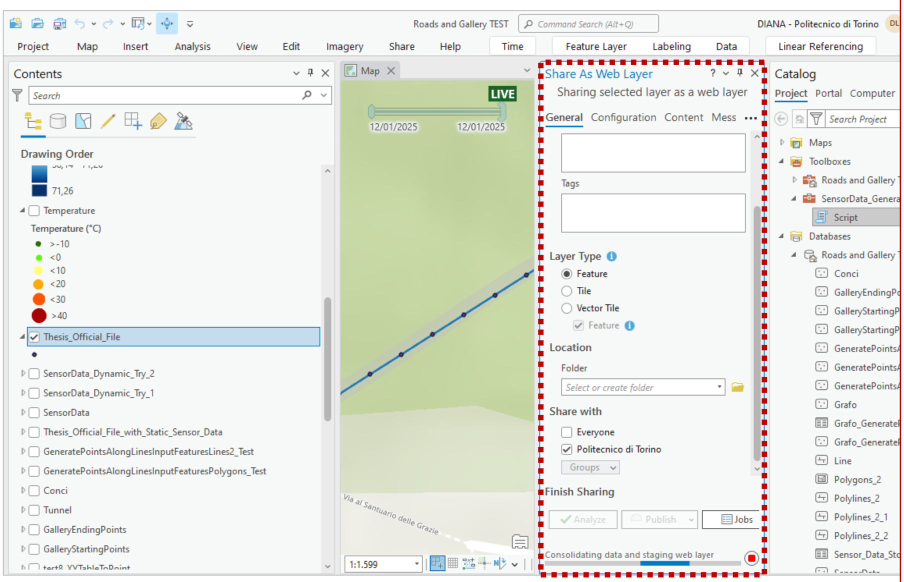
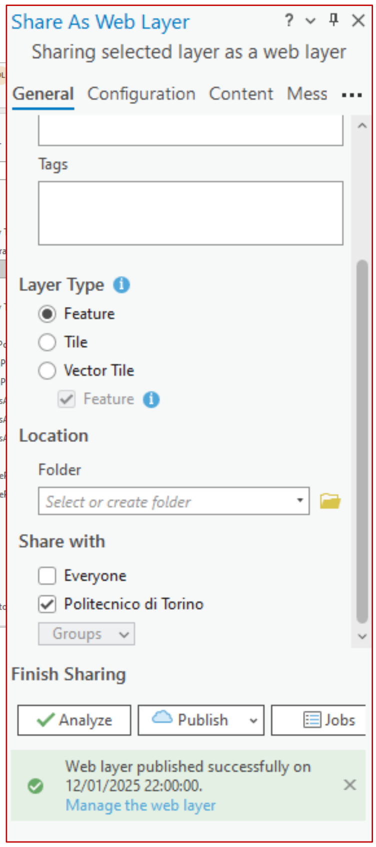



Figure 40. Successfully published Web Layer

B. Creation of the Web Map

- ✓ Log In to ArcGIS Online
- ✓ Create a new Web Map

In ArcGIS Online, by clicking in the Map option from the top menu, a new map is created. The published feature layer, including the script which in the background supplied real-time sensor data is added to the map by following the sequence: *Add > Search for the layer > Choosing the hosted feature layer.*

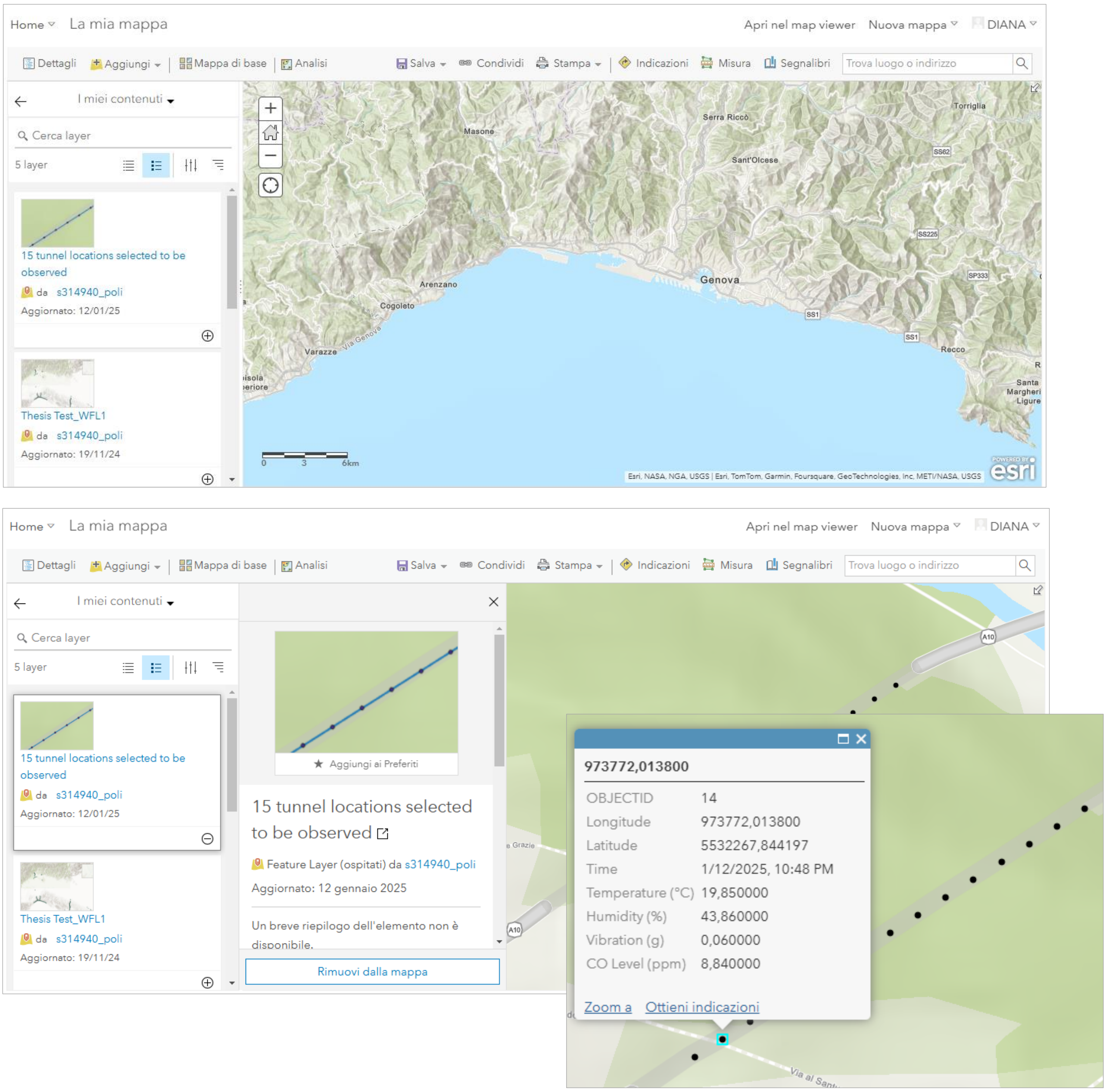


Figure 41. Map published online - various stages

✓ Map customization

Adjusting the basemap, symbology and any other settings, keeping in mind the final product which has to be achieved.

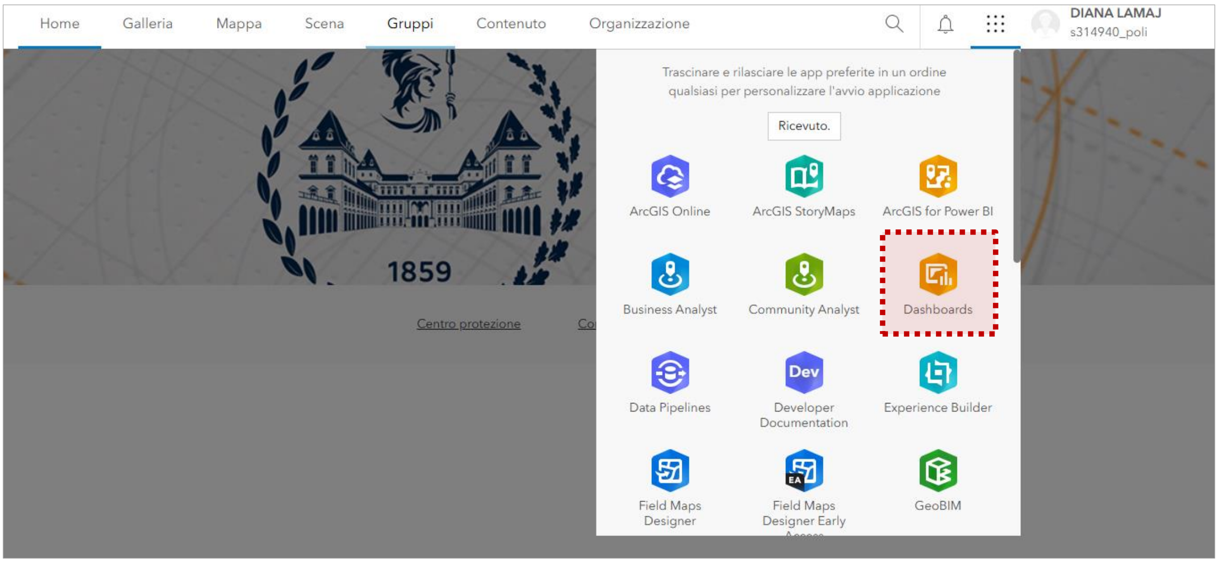
✓ Save the map

Save > *Save* As and the map is given a name, tags, and description, based on the preference.

C. Creation of the Dashboard

✓ Create a new Dashboard

In the ArcGIS Online Home page, clicking on Apps in the top menu and selecting Dashboard from the available options.



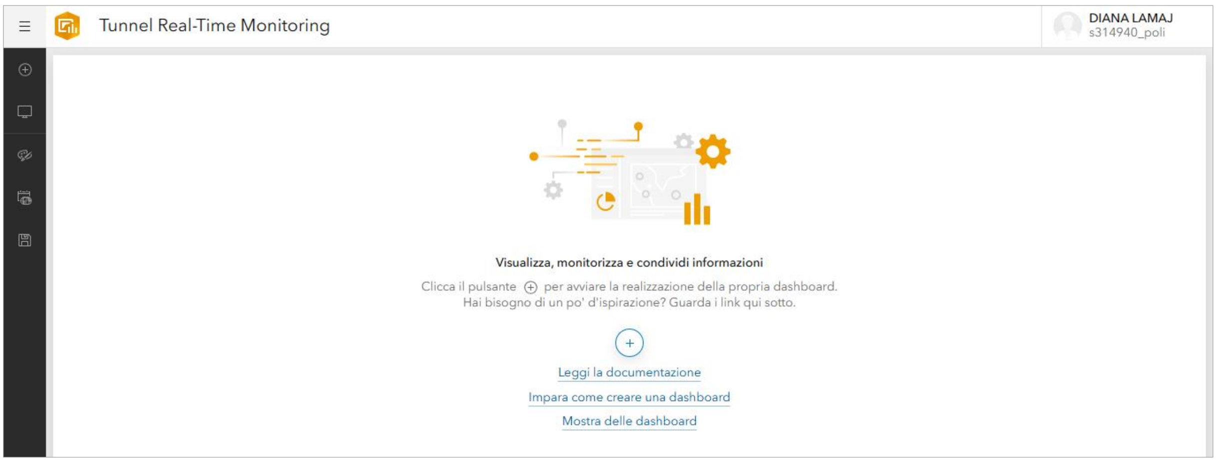


Figure 42. Dashboard creation and first view

✓ Adding the Web Map to the Dashboard

The web map which was created previously is added by selecting *Add > Map* and then selecting the map. The map appears on the left-hand side of the dashboard design space.

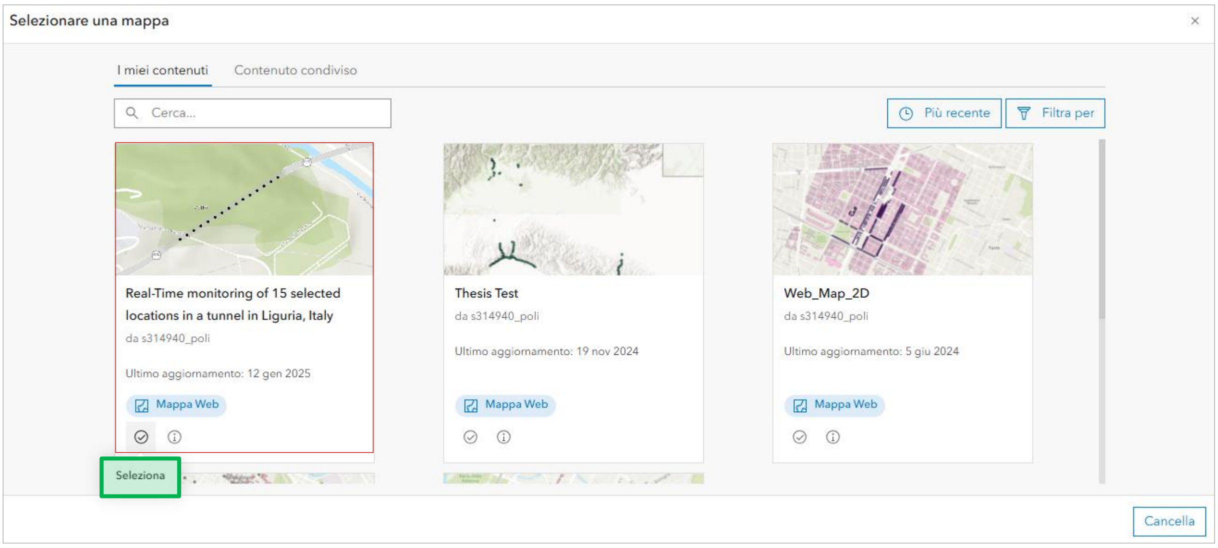


Figure 43. Adding the map to the Dashboard

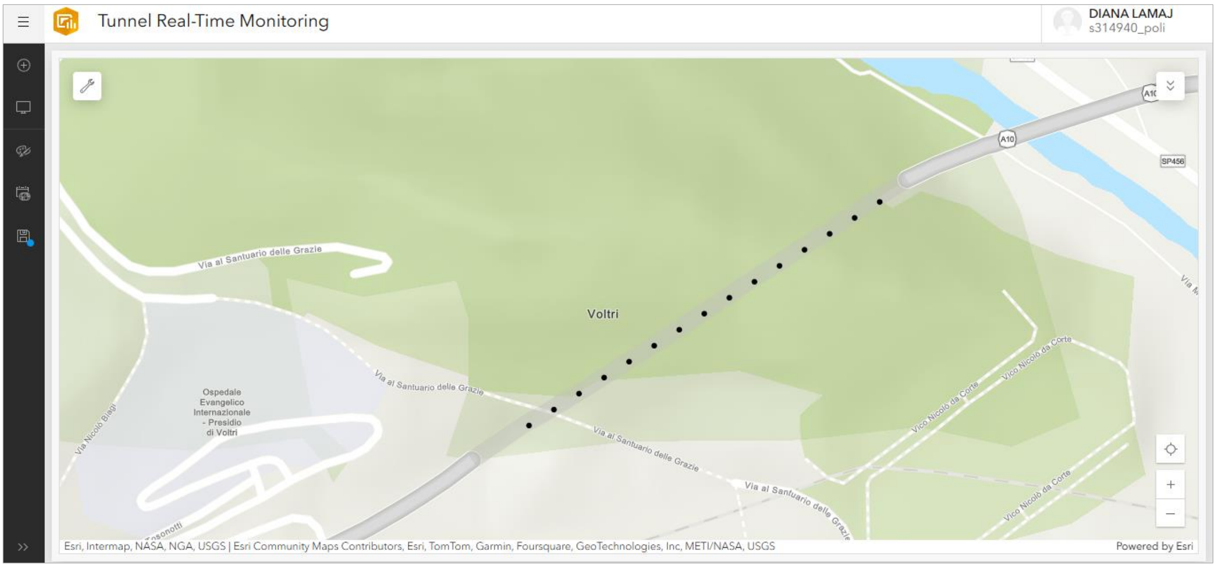


Figure 44. Dashboard's first view with the map included

- ✓ Adding widgets to visualize the data

Various gadgets can be experimented with to choose the ones that better fit the required way the parameters have to be expressed.

- ✓ Configure real-time updates

At any time, must be made sure that the map and the dashboard widgets are set to refresh dynamically with new data as it is added. This can be set in the widget or map settings under the refresh interval.

- ✓ Customize the layout

The widgets are rearranged and resized accordingly, to create an optimal layout, clean and user-friendly. Additionally, final touches are made such as headers, text and design elements which guide the users through the dashboard.

D. Configuration and publishing of the Dashboard

- ✓ Dashboard testing

By previewing the dashboard and ensuring all the widgets are working properly and most importantly, the real-time data update is functioning as expected.

- ✓ Dashboard publishing

After completing the setup, by clicking **Save,** the dashboard is saved. Then Share and here the sharing preferences are selected. Considering how this dashboard was created as part of a thesis, it was shared with my organization, which is Politecnico di Torino.

- ✓ Dashboard accessing

Now that the dashboard is published, it can be accessed from ArcGIS Online and is shareable with other parties by simply providing its link.

E. Monitoring and adjusting the Dashboard

- ✓ Dashboard's performance review

By performing period checks, as the dashboard's creator, I can make sure that it's updating real-time, as intended. Changes with the refresh rate or widgets can be done, if necessary.

- ✓ Fine-tuning of the design

Considering how this proposal can be implemented, depending on user feedback, there might be a need to refine the dashboard's layout or removal/addition of widgets to allow deeper insights.

5.5. Data visualisation

With the base work being done, next is the definitive data visualisation which was a process of constant back and forth selections. To recap the previous steps which have enabled this final one: needed layers dedicated to each monitored parameter are created and being fed data correctly from the real-time sensor mimicking python script, the map in ArcGIS Online is created and can be modified and enrichened with the layers as the author desires and the Dashboard has been also created and the map can be easily imported and gadgets chosen accordingly.

The data can be visualised in 2 ways:

1. Using ArcGIS Pro Software
2. Using Dashboards by ArcGIS

Below shall be presented the data visualisation in both ways. 1st way is illustrated in 4 videos which show how each layer can be monitored real time to take decisions, based on the strategies described in the previous sections, based on each user category. 2nd way is illustrated with a sequence of imagines which are taken from the definitive Dashboard. To reach the actual data, the full project, Dashboard link and YouTube link of the videos are provided.

YouTube Link https://youtu.be/JHBT7sDDY60

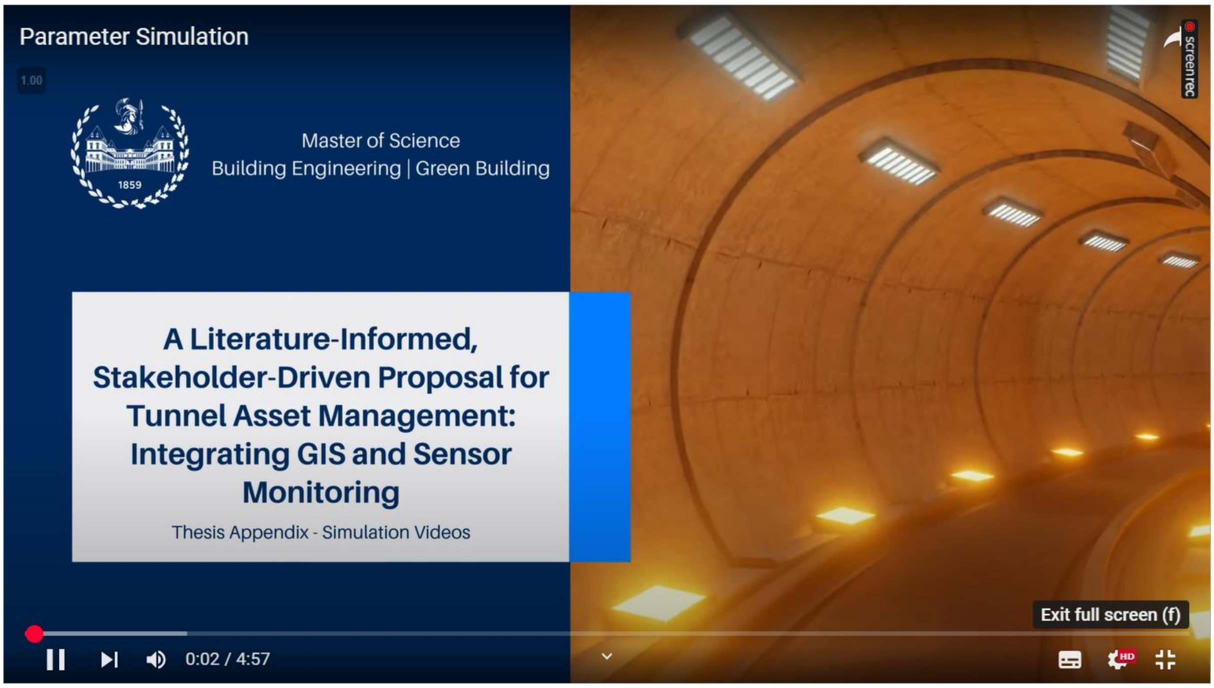


Figure 45. Simulation video as seen in YouTube

DASHBOARD Link https://www.arcgis.com/apps/dashboards/cfd72c75e6374c7e891e7b4871601873

Figure 46. Dashboard

6. Discussion

This section analyses the developed proposal and broader thesis concept for tunnel monitoring while addressing its strengths and limitations and proposes enhancements to increase its operational capability.

6.1. Strength and limitations

Strengths

Overall, this thesis can be considered an experimental one because it tried to bring a fresh and innovative approach to the way assets can be managed, removing the borders of the existing classic siloed data and holding the potential to expand to a broader target of assets, rather than the tunnel ones for which it was demoed.

The fundamental strength of the final product, stands in its power to bring change and strive to push the progress a bit further, serving as an inspiration for anyone who has the curiosity and desire to perfect it in the future and expand it, potentially giving it a universal use and functionality. This product aims to make a small, but real change in the life and work of those directly affected: the stakeholders. This said, it is driven by the need that the life of an engineer has, to help build the world and make everything better and more efficient. Therefore, not only brings in a collective way a literature-review, to assist any beginner who is trying to receive more information on this topic which isn't a typical studied-at-the-university one, but also tries to make a small, yet probably highly significant change to the real life of the real involved persons.

As for technical strengths and interesting proposal points in the field, the following can be mentioned.

- ✓ Centralized Data Integration: The dashboard combines data sources coming from multiple sensors to create one integrated platform where stakeholders, especially the O&M teams, can access asset information both in real time and as historical records. This integration facilitates efficient data management and retrieval, essential for informed decision-making. This results in improving the time factor, the human resources and the monetary ones.
- ✓ Real-Time Monitoring: The incorporation of real-time data feeds integrated into the system enables instant anomaly detection which leads to proactive maintenance solutions

that decrease infrastructure failure risk. Again, there is a triple positive effect, because there's navigated easily the service interruption that might be causes by any trouble whatsoever, the financial resource allocation is done in a more structured, studied and data supported way, and the employees aren't subjected to routine checks that might impose various sorts of threats in case of lack of actual real-data from the underground.

- ✓ User-Friendly Interface: Simplicity remains the cornerstone of design for this interface which allows stakeholders, regardless of their technical expertise, to understand and interpret the data effectively through navigation. Utilizing the numerous gadgets, not only the employees improve their work life, but also the upper-level decision making meetings can be easily assisted and supported by the data which is already represented in such way to make the situation easily readable, enabling so improved communication and decision-making.

Limitations

As an experimental and innovative thesis, the final product has limitations, and in the quality of the ideator and developer the following can be said:

The lack of presence of real sensor data made the realisation of the concept a little more challenging than what it was predicted to be. The data had to be simulated, with some background research about the values and limits. Nevertheless, since the data is simulated and hypothesized it might not match the reality of the parameters of temperature, humidity, vibrations and hazardous gases in tunnels. The purpose was to be able to visualise and show to the audience the way in which tunnel asset management can be elevated, and the fact that the hypothesized data might not match the real ones, doesn't hold any importance whatsoever in this sense, because assuming such proposal comes to life and it's applied in the future, the data will be actually taken from real measurements and the visualisation way will still be the same.

The situation changes, when it comes to the way IoT and GIS collaborate to make the visualisation a reality. Assuming there are real sensors connected to the tunnels, all the sensor data would be stored in another way, depending on the sensor supplier and the sensor design itself. These data, could be still connected to the georeferenced points in ArcGIS Pro, using a Python script, but the script would of course, be different, matching the location of the stored real sensor data. The scripts developed for this thesis, both the classic and fire simulation one, accommodate the simulated sensor data and allow their connection of the tunnel locations. Again, nothing would change in the logic behind the visualisation, but the detailed way in which this would be completed, would be certainly different.

Lastly, the Dashboard produced to illustrate the concept of the whole, is static, because the information is shared from the software as a Web Layer, and its information it can't be dynamically connected to the Dashboard. Were the sensor data, stored online, in a cloud or else, the connection to the Dashboard, would be managed differently, technically speaking, and the final product would be dynamic.

Some of the technical limitations that can be mentioned regarding the concept are the following:

- Data Accuracy and Completeness: The system depends on accurate and complete input data for proper reliability to function. The usage of incomplete and/or inaccurate data can produce wrong decisions and assessment results.
- Scalability Issues: Implementation of the system for one single tunnel works well but when attempting to scale to multiple infrastructures users may encounter issues regarding data control and system performance.
- Integration with Existing Systems: The integration process between the dashboard and pre-existing asset management systems can be complex which might result in data silos unless the implementation is properly managed.

6.2. Potential improvements

1. Enhanced Data Validation: Data validation systems strengthening is essential for maintaining accurate and reliable data collections. Through the reduction of errors and inconsistencies these protocols create more trustworthy outputs which advance the decisive processes within Tunnel Asset Management.
2. Scalability Enhancements: The system needs architectural optimization to effectively process bigger datasets when achieving scalability goals. A system architecture based on adaptable frameworks can allow the proposed solution to scale across multiple infrastructures and maintain operational efficiency simultaneously with system performance.

3. Advanced Analytical Tools: Through predictive analytics integration organizations gain improved capabilities to detect infrastructure and operational problems in advance of their escalation. The integration of machine learning models combined with data-driven insights enables proactive maintenance approaches that reduce downtime and optimize resource allocation.
4. Improved Integration Capabilities: The establishment of standardized APIs enables smooth communication with existing infrastructure management systems while enabling data sharing among different stakeholders. API standardization creates an integrated system that reduces repetition while enhancing teamwork between stakeholders thus improving the approach to TAM.

To wrap it up, it can be said that the need and desire of the author to provide a product which holds the potential to help the stakeholders, it was successfully done, to her liking. All the same, the author recognizes the limitation of her proposal and acknowledges that future work can be performed to change it, perfect it, and potentially apply it.

7. Conclusion and future work

The work conducted within the scope of this thesis introduces innovative Tunnel Asset Management (TAM) insights by combining GIS-based sensor monitoring techniques alongside stakeholder-driven approaches. This proposed methodology develops a new asset management strategy to create a unified monitoring system while bridging traditional data silos into an interactive and efficient platform. The major achievement of this work lays in its capability to combine asset data management while providing stakeholders with an easy-to-use Dashboard which enhances real-time observation abilities for better decision-making processes. This framework enables proactive maintenance approaches through which infrastructure breakdowns can be minimized as a result of optimized resource deployment and safer working environments for all stakeholders. The system's ability to combine multiple sensor data types and make sensor information easy to view becomes the building block for improving TAM and other infrastructure control systems.

Experimental research comes with its limitations despite providing effective results. The usage of simulated sensor information in experimentation for concept demonstrations makes it difficult to achieve complete replication of actual world environmental conditions. Implementation of the dashboard requires further improvements concerning its static nature while maintaining data accuracy and scalability for successful large-scale application. Seamless interoperability demands well-structured solutions because integrating the system with existing asset management platforms turns out to be complex. This thesis outlines both theoretical elements and technical specifications for the proposed system alongside defined improvements which can guide further development. The system's functional capabilities alongside its real-world applications will experience significant enhancement through data validation improvement alongside scalability enhancement and predictive analytics integration.

7.1. Key findings and contributions to the field

The developed GIS-based Dashboard proves how GIS technology integration with IoT into infrastructure asset management works efficiently. Key contributions include:

1. Demonstrated integration of GIS and IoT in, and for the asset management
2. Proactive maintenance facilitation resulting in enhanced human, time, and monetary resource management

3. User accessibility: the real involved parties are the main drive

The project exhibits how GIS implements centralized asset management by utilizing maps for optimization of decision processes. Through real-time monitoring the system supports a transition from reactive to proactive maintenance which totals to enhanced infrastructure asset longevity. The system interface successfully achieves broad stakeholder engagement because its user-friendly design makes it accessible to multiple user categories.

7.2. Future prospects

Building upon the current work, future endeavours could focus on:

1. Incorporation of Machine Learning
2. Expansion to other infrastructure types
3. User feedback integration
4. Sustainability metrics inclusion

The use of Machine Learning algorithms can help analyse historical data and usage patterns to predict necessary maintenance procedures. Its development plan includes extending its capabilities to include monitoring and management functions for a complete asset management platform that covers bridges and highways alongside other infrastructure types. The system also holds the potential to receive user feedback for continuous development which improves both system functionality and user experience. Lastly, it can incorporate sustainability metrics through environmental impact assessments which support sustainable infrastructure management.

Through this work the author demonstrates complete dedication to both innovation and practical solutions that benefit stakeholders within TAM. The presented conceptual model aims to inspire field development through its demonstrative approach by serving as a foundation for future benchmarking of actual field implementations.

REFERENCES

[1] N. Almeida, M. Trindade, D. Komljenovic and M. Finger, “A conceptual construct on value for infrastructure asset management,” *Utilities Policy,* vol. 75, no. 101354, 2022.

[2] S. K. Sinha and S. S. Eslambolchi, “Bridging the Gap: An Educational Primer on Sustainable Water Infrastructure Asset Management,” Asset Management Primer © Penn State, University Park, PA, 2006.

[3] E. M. H. Ismaeil, “Asset Information Model Management-Based GIS/BIM Integration in Facility Management Contract,” *Sustainability,* vol. 16(6), no. 2495, 2024.

[4] S. Caldera, S. Mostafa, C. Desha and S. Mohamed, “Exploring the Role of Digital Infrastructure Asset Management Tools for Resilient Linear Infrastructure Outcomes in Cities and Towns: A Systematic Literature Review,” *Sustainability,* vol. 13(21), no. 11965, 2021.

[5] “BSI,” 2004. [Online]. Available: https://www.bsigroup.com/en-GB/.

[6] ISO/TC 251, “International Organization for Standardization,” 01 2014. [Online]. Available: https://www.iso.org/standard/55088.html.

[7] J. Rymsza, “Causes of the Collapse of the Polcevera Viaduct in Genoa, Italy,” *Applied Sciences,* vol. 11(17), no. 8098, 2021.

[8] M. Morgese, F. Ansari, M. Domaneschi and G. P. Cimellaro, “Post-collapse analysis of Morandi’s Polcevera viaduct in Genoa Italy,” *Journal of Civil Structural Health Monitoring,* vol. 10(3), p. 69–85, 2020.

[9] Directorate-General for Mobility and Transport (DG MOVE) , «Transport in the European Union: Current Trends and Issues,» European Commission, Brussels, 2019.

[10] H. Liu, P. E. Love, J. Zhao, C. Lemckert ve K. Muldoon-Smith, «Transport Infrastructure Asset Resilience: Managing Government Capabilities,» *Transportation Research Part D: Transport and Environment,* 2021.

[11] LNCE, European Workshop on Structural Health Monitoring, vol. 254, Cham, Switzerland: Springer Nature Switzerland AG, 2022.

[12] ASCE, “Report Card for America's Infrastructure: Infrastructure Investment Gap 2020-2029,” 2021.

[13] A. Tarazona, M. Coelho, S. Fernandesa and J. Matos, “Transport infrastructure risk management in the context of climate change: policies, challenges, and opportunities,” *Transportation Research Procedia,* vol. 72, pp. 1404-1411, 2023.

[14] Core Writing Team, H. Lee and J. Romero (eds.), “ Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,” IPCC, Geneva, Switzerland, 2023.

[15] B. Allen, P. Ram, K. Zimmerman and O. Smadi, Handbook for Including Ancillary Assets Transportation Asset Management Programs, Office of Infrastructure Research and Development, 2019.

[16] EEC, “Economic losses from weather- and climate-related extremes in Europe,” [Online]. Available: https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related. [Accessed 06 10 2023].

[17] K. C. Sinha, S. Labi and B. R. D. K. Agbelie, “Transportation infrastructure asset management in the new millennium: continuing issues, andemerging challenges and opportunities,” *Transportmetrica A: Transport Science,* vol. 13, no. 7, pp. 591-606, 2017.

[18] H. Liu, P. E. Love, J. Zhao, C. Lemckert and K. Muldoon-Smith, “Transport Infrastructure Asset Resilience: Managing Government Capabilities,” *Transportation Research Part D: Transport and Environment,* 2021.

[19] N. E. Lownes, A. M. Zofka and A. Pantelias, “Moving Toward Transportation Asset Management,” *Public Works Management & Policy,* vol. 15, no. 1, pp. 4-19, 2010.

[20] J. Bittner and H. Rosen, “Transportation Asset Management Overview,” *Public Works Management & Policy,* vol. 8, no. 3, pp. 151-155, 2004.

[21] S.-A. Mitoulis, D. V. Bompa and S. Argyroudis, “Sustainability and climate resilience metrics and trade-offs in transport infrastructure asset recovery,” *Transportation Research,* vol. Part D, no. 121, p. 103800, 2023.

[22] R. Vakili, A. Herzog and P. Lund, “Geo-Structural Challenges for Advancing Tunnel Design and Construction,” *STRUCTURE,* pp. 12-14, December 2019.

[23] Permanent International Association of Road Congresses (PIARC), Road tunnels manual, Puteaux: PIARC, 2019.

[24] E. Fischer, “Railway Technology,” [Online]. Available: https://www.railway-technology.com/features/featurefiring-up-rail-tunnel-safety/?cf-view. [Accessed 5 October 2011].

[25] E. Hupje, “9 Types of maintenance: How to choose the right maintenance strategy,” [Online]. Available: https://reliabilityacademy.com/types-of-maintenance/.

[26] T. Blumenfeld, M. Stöckner, L. Liu, R. Hajdin, M. König and K. Gavin, “Concepts for the Integration of Data from Asset Management Systems into BIM,” *Transportation Research Procedia,* vol. 72, p. 3738–3745, 2023.

[27] L. B. Machado and M. M. Futai, “Tunnel performance prediction through degradation inspection and digital twin construction,” 2023.

[28] R. Hajdin, R. Richter, L. Rakic, H. Diederich, J. Hildebrand, S. Schulz, J. Döllner and J. Bednorz, “Digitalization of bridge inventory via automated analysis of point clouds for generation of BIM models,” *EUROSTRUCT 2023:European Association on Quality Control of Bridges and Structures: Digital Transformation in Sustainability,* vol. 6, no. 5,

pp. 1189-1197, 2023.

[29] G. Karmakar, J. Kamruzzaman, S. Islam, G. Chattopadhyay and R. Pai, “Internet of Things for Asset Management: Data Analytics and Security,” 2020.

[30] Iowa Section of the ASCE, “Report Card for Iowa's Infrastructure,” ASCE, Iowa, 2019.

[31] O. Abdelhady and M. Osama, “Condition Monitoring of Reinforced Concrete Bridge Decks: Current Practices and Future Perspectives,” *Current Trends in Civil & Structural Engineering,* vol. 8, no. 4, 2022.

[32] “Reactive Maintenance Vs Preventive Maintenance: A Comparative Analysis,” [Online]. Available: https://facilio.com/blog/reactive-maintenance-vs-preventive-maintenance/. [Accessed 1 February 2024].

[33] A. Gwilliam, “Preventive Maintenance vs. Reactive Maintenance: Do You Have to Choose?,” [Online]. Available: https://www.getmaintainx.com/blog/preventive-maintenance-vs-reactive-maintenance. [Accessed 5 May 2020].

[34] European Comission Directorate-General for Climate Action, “Consequences of climate change,” [Online]. Available: https://climate.ec.europa.eu/climate-change/consequences-climate-change_en#threats-to-business.

[35] E. Fleming, J. Payne, W. Sweet, M. Craghan, J. Haines, J. F. Hart and H. S. A. Sutton-Grier, “Coastal Effects,” *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment,* vol. 2, pp. 322-352, 2018.

[36] ABC News, “Flooded UK tunnel causes mass train cancellations, stranding hundreds of New Year travellers,” ABC News, [Online]. Available: https://www.abc.net.au/news/2023-12-31/flooded-tunnel-causes-eurostar-cancellations-stranded-travellers/103275314. [Accessed 30 12 2023].

[37] K. Anderson, T. Grove, P. Allen, S. Fiala, E. Habic, B. Lupes, J. Rozum, M. Okter, C. Buckel and T. Meckley, “Resilient Coastal Roads,” [Online]. Available: https://storymaps.arcgis.com/stories/d85e1b18c82a4e40b7722ef195bf79cd.

[38] USGS, “Coasts, Storms, and Sea Level Rise,” [Online]. Available: https://www.usgs.gov/science/science-explorer/climate/coasts-storms-and-sea-level-rise.

[39] J. Wassmer, B. Merz and N. Marwan, “Resilience of transportation infrastructure networks to road failures,” *Chaos,* vol. 34, p. 013124 , 2024.

[40] OECD, “Infrasutrcture for a Climate-Resilient Future,” OECD Publishing, Paris, 2024.

[41] J. L. Miramontes, “Transportation Network Resilience: Evaluation of Performance Measures,” *Open Access Theses & Dissertations,* vol. 904, 2016.

[42] H. Duijnhoven, A. Nieuwenhuijs, P. v. d. Brink, D. Stolk and T. v. Ruijven, “Critical infrastructure resilience: bridging the gap between measuring and governance,” *7th REA Symposium,* vol. 141, p. 198, 2017.

[43] D. Rehak, L. Flynnova, M. Hromada and C. Fuggini, “The Importance of Resistance in the Context of Critical Infrastructure Resilience: An Extension of the CIERA Method,” *Systems,* vol. 11, no. 506, 2023.

[44] W. Liu, M. Shan, S. Zhang, X. Zhao and Z. Zhai, “Resilience in Infrastructure Systems: A Comprehensive Review,” *Construction Management and Disaster Risk Management,* vol. 12, no. 6, p. 759, 2022.

[45] J. Schofer, S. DesRoches and P. Bocchini, “Investing in Transportation Resilience: A Framework for Informed Choices,” 19 October 2021. [Online]. Available: https://onlinepubs.trb.org/onlinepubs/webinars/211019.pdf.

[46] F. Beckers, N. Chiara, A. Flesch, J. Maly, E. Silva and U. Stegemann, “A risk-management approach to a successful infrastructure project,” *McKinsey Working Papers on Risk,* vol. 2, 2013.

[47] “Predictive Maintenance With IoT: A Comprehensive Guide,” Rejig Digital, [Online]. Available: https://www.rejigdigital.com/blog/predictive-maintenance-iot-comprehensive-guide/. [Accessed 2024].

[48] L. Collier, “How predictive maintenance can protect infrastructure during extreme weather,” TECH MONITOR 30, [Online]. Available: https://www.techmonitor.ai/comment-2/predictive-maintenance-extreme-weather?cf-view%20https://llumin.com/predictive-maintenance-analytics-improve-efficiency-and-reduce-unplanned-downtime-llu/&cf-view. [Accessed 22 February 2024].

[49] C. Stalder, G. Ducellier and M. Lewkowicz, “The implementation of a digital twin as an intelligent asset management system of a railway infrastructure: application to the work scheduling process at SNCF Réseau,” *Transportation Research Procedia,* vol. 72, p. 2302–2308, 2023.

[50] C. Gragnaniello, G. Mariniello, T. Pastore and D. Asprone, “BIM-based design and setup of structural health monitoring systems,” *Automation in Construction,* vol. 158, p. 105245, 2024.

[51] “Open Web Technology,” [Online]. Available: https://www.owt.swiss/en/cases/empowering-digitalization-gotthard-base-tunnel-augmented-reality.

[52] ESRI, Modernizing Asset Management with Location Intelligence, California.

[53] R. Mutuli, “ESRI Eastern Africa,” ESRI, [Online]. Available: https://www.blog.esriea.com/harnessing-the-power-of-arcgis-for-efficient-asset-management/. [Accessed 11 September 2023].

[54] ESRI UK, “ESRI UK,” ESRI, [Online]. Available: https://www.esriuk.com/en-gb/industries/transportation/overview.

[55] ESRI, “A Practical Guide to GIS in Asset Management,” California, 2017.

[56] A.-Q. Gbadamosi, L. O. Oyedele, J. M. D. Delgado, H. Kusimo, L. Akanbi, O. Olawale and N. Muhammed-yakubu, "IoT for predictive assets monitoring and maintenance: An implementation strategy for the UK rail industry," *Automation in Construction,* vol. 122, p. 103486, 2021.

[57] S. M. Bartram, J. Branke and M. Motahari, Artifical Intelligence in Asset Management, Virginia: CFA Institute Research Foundation, 2020.

[58] D. Sarkar, H. Patel and B. Dave, "Development of integrated cloud-based Internet of Things (IoT) platform for asset management of elevated metro rail projects," *International Journal of Construction Management,* vol. 22, no. 10, pp. 1993-2002, 2022.

[59] L. Oneto, M. Anastasopoulos, D. Anguita, I. Baroni, R. Canepa, C. Dambra, S. Gogos, W. Jentner and S. Petralli, "DAYDREAMS - Development of Prescriptive Analytics based on Artificial Intelligence for Railways Intelligent Asset Management Systems," *Transportation Research Procedia,* vol. 73, pp. 478-485, 2023.

[60] R. Pell, R. Svoboda, R. Eagar, P. Ondko and F. Kirschnick, "Effective Infrastructure Asset Management," *Arthur D. Little,* 2015.

[61] S. Caldera, S. Mostafa, C. Desha and S. Mohamed, "Exploring the Role of Digital Infrastructure Asset Management Tools for Resilient Linear Infrastructure Outcomes in Cities and Towns: A Systematic Literature Review," *Sustainability,* vol. 13, no. 21, p. 11965, 2021.

[62] T. McDonald, M. Robinson and G. Tian, "T-Vision: A hybrid subsurface radar inspection system for intelligent asset management of railway tunnels," *Transportation Research Procedia,* vol. 72, pp. 3466-3473, 2023.

[63] M. Garramone, N. Moretti, M. Scaioni, C. Ellul, F. R. Cecconi and M. C. Dejaco, "BIM AND GIS INTEGRATION FOR INFRASTRUCTURE ASSET MANAGEMENT: A BIBLIOMETRIC ANALYSIS," *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 2020.

[64] S. Amirebrahimi, A. Rajabifard, P. Mendis and T. D. Ngo, "A data model for integrating GIS and BIM for assessment and 3D visualisation of flood damage to building," 2014.

[65] Y. Deng, J. C. P. Cheng and C. J. Anumba, "Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison," *Automation in Construction,* vol. 67, no. 2, pp. 1-21, 2016.

[66] A. Borrmann, M. König, C. Koch and J. Beetz, Building Information Modeling Technology Foundations and Industry Practice: Technology Foundations and Industry Practice, 2018.

[67] J. Zhu, G. Wright, J. Wang and X. Wang, "A Critical Review of the Integration of Geographic Information System and Building Information Modelling at the Data Level," *ISPRS International Journal of Geo-Information,* vol. 7, no. 2, p. 66, 2018.

[68] R. Fosu, K. Suprabhas, Z. Rathore and C. Cory, “Integration of Building Information Modeling (BIM) and Geographic Information Systems (GIS) – a literature review and future needs,” 2015.

[69] U. Isikdag, S. Zlatanova and J. Underwood, “A BIM-Oriented Model for Supporting Indoor Navigation Requirements,” *Computers, Environment and Urban Systems,* vol. 41, pp. 112-123, 2013.

[70] K. Ku and M. Taiebat, “BIM Experiences and Expectations: The Constructors' Perspective,” *International Journal of Construction Education and Research,* vol. 7, no. 3, pp. 175-197, 2011.

[71] “Structural health monitoring,” Wikipedia, [Online]. Available: https://en.wikipedia.org/wiki/Structural_health_monitoring. [Accessed 2024 08 2024].

[72] W. Liu, X. Wu, L. Zhang, Y. Wang and J. Teng, “Structural Health-Monitoring and Assessment in Tunnels: Hybrid Simulation Approach,” *Journal of Performance of Constructed Facilities,* vol. 34, no. 4, p. 04020045, 2020.

[73] Neuvition, Inc, “How Crucial Is LiDAR For Tunnel Detection?,” Neuvition, Inc, [Online]. Available: https://cdn.neuvition.com/media/tunnel-detection.html. [Accessed 27 02 2023].

[74] ACKCIO, “Real-Time Monitoring of an MRT Tunnelling Project in Singapore,” ACKCIO, [Online]. Available: https://www.ackcio.com/case-studies/real-time-monitoring-of-an-mrt-tunnelling-project-in-singapore/.

[75] SOLIFOS, “Solifos Supplies Sensor Cables for the Brenner Base Tunnel – the World’s Longest Railway Tunnel Project,” SOLIFOS, [Online]. Available: https://solifos.com/en/brenner-base-tunnel-monitoring/. [Accessed 21 08 2024].

[76] ENCARDIO RITE, “Tunnel monitoring: Advaced survey and monitoring systems,” ENCARDIO RITE, [Online]. Available: https://www.encardio.com/blog/tunnel-monitoring-survey-and-monitoring-sensors.

[77] move SOLUTIONS, “Smart Structural Health Monitoring,” move SOLUTIONS, [Online]. Available: https://www.movesolutions.it/.

[78] AASHTO, “AASHTO Transportation Asset Management Guide”.

[79] S. Bhamidipati, “Simulation framework for asset management in climate-change adaptation of transportation infrastructure,” *Transportation Research Procedia,* vol. 8, no. 2015, pp. 17-28, 2015.

[80] P. E. Love, L. A. Ika, J. Matthews, X. Li and W. Fang, “A procurement policy-making pathway to future-proof large-scale transport infrastructure assets,” *Research in Transportation Economics,* vol. 90, no. 2021, p. 101069, 2021.

[81] I. Hoff, I. Alovisi, A. B.-v. Vliet, P. Darò, F. Fliegel, J. Köhler, F. Liljefors, S. C. Navas, E. Scibilia, A. Straus, M. Weise, J. Wessels and J. Żach, “Analyses of barriers, trends and best practices for better monitoringand maintenance of European transport

infrastructure," *Transportation Research Procedia,* vol. 72, pp. 343-350, 2023.

[82] A. Mohammad, L. Amador-Jimenez and F. Nasiri, "Review of asset management for metro systems: challenges and opportunities," *Transport Reviews,* pp. 1464-5327, 2018.

[83] N. Hoult and K. Soga, "Sensing solutions for assessing and monitoring tunnels," in *Sensor Technologies for Civil Infrastructures (Second Edition)*, Woodhead Publishing Series in Civil and Structural Engineering, 2022, pp. 135-173.

[84] Leica Geosystems AG - Part of Hexagon, "Monitoring for tunnels," Leica Geosystems AG - Part of Hexagon, [Online]. Available: https://leica-geosystems.com/industries/monitoring-solutions/transportation-infrastructure/monitoring-for-tunnels. [Accessed 2025].

[85] "US Climate Resilience Toolkit," [Online]. Available: https://toolkit.climate.gov/topics/built-environment/transportation. [Accessed 5 August 2021].

[86] wsp, "Asset Management," wsp, [Online]. Available: https://www.wsp.com/en-gl/hubs/asset-management.

[87] Associated Press, "Investigators find third victim from fiery Wyoming highway tunnel crash," Associated Press, [Online]. Available: https://apnews.com/article/wyoming-highway-tunnel-crash-3rd-victim-c327d0596f749f94b230dbd71830da43. [Accessed 16 02 2025].

[88] H. Yu, J. Chen, A. Bobet and Y. Yuan, "Damage observation and assessment of the Longxi tunnel during the Wenchuan earthquake," *Tunnelling and Underground Space Technology,* vol. 54, pp. 102-116, 2016.

[89] Y. Fujino and D. Siringoringo, "Recent research and development programs for infrastructures maintenance, renovation and management in Japan," *Structure and Infrastructure Engineering ,* vol. 16, no. 2, pp. 1-23, 2019.