Community-Based Smart City Digital Twin Platform

for Optimised DRM operations and Enhanced Community

Disaster Resilience

D3.3

SCDT Conceptual Model

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Author(s)	Fanourios Fakoukakis (FINT), Daniel Dimitriou (FINT), Andreas Tsarouchas (FINT), Michael Karamousadakis (THL), George Stergiopoulos (THL), Jean-Philippe Crepin (M3SB), Vassiliki Apostolopoulou (PRACTIN), Sotirios Nakos (INTEROPTICS), Dimitrios Petridis (EPSILON)
Internal reviewer(s)	Fanourios Fakoukakis (FINT), Sotirios Nakos (INTEROPTICS), Constanze Geyer (JOAFG), Otilia Bularca (SIMAVI), Ana-Maria Dumitrescu (SIMAVI)
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TASK ABSTRACT

Task 3.3 "Conceptual Model of Smart Cities with Digital Twins (SCDT) for Disaster Management" addresses the design of the SCDT model for community-based disaster management. The aim of the work is to create the model, utilising smart cities and digital twin technologies. Following WP2 outcomes regarding the community characteristics and the identified disaster scenarios, the model incorporates the advanced

[1] **Please indicate the type of the deliverable using one of the following codes**:
R = Document, report
DEM = Demonstrator, pilot, prototype, plan designs
DEC = Websites, patents filing, press & media actions, videos
DATA = data sets, microdata
DMP = Data Management Plan
ETHICS: Deliverables related to ethics issues.
OTHER: Software, technical diagram, algorithms, models, etc.

[2] **Please indicate the dissemination level using one of the following codes**:
PU = Public
SEN = Sensitive

sensing technologies to be exploited in the PANTEHON project, in order to provide a system-level technological framework for information gathering and provisioning, and enhance decision-making and management processes of the relevant stakeholders and disaster management authorities.

REVIEW HISTORY

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EXECUTIVE SUMMARY

This deliverable constitutes the outcome of Task 3.3 "Conceptual Model of Smart Cities with Digital Twins". The objective of the deliverable is to provide the design and analysis of the Smart City Digital Twin (SCDT) model for community-based disaster management. The model was designed based on the envisaged PANTHEON architecture and the work performed so far in WP2 and WP3.

PANTHEON will implement a platform for community-based disaster risk management, founded on the exploitation of advanced technologies, such as in-situ and remote sensing, big data analytics, Artificial Intelligence (AI), smart cities and digital twins. For that reason, a system-level model of the SCDT must be designed, in order to provide the basis for the development of the PANTHEON general architecture and the individual technological components which is consisted of.

The document commences with an introduction about the work performed and the deliverable sections. The sections structure is based on the SCDT model architecture, which is analyzed in detail. Initially, the general Smart City concept is provided, along with a dedicated section regarding Smart Cities for Disaster Management. The Digital Twin technology is described to provide the basis for further SCDT analysis. Subsequently, a large part of the deliverable is dedicated to the description and analysis of the SCDT and its components, including the technologies, such as sensing/monitoring, AI and data analysis, along with characteristics of the community.

Lastly, additional information about the PANTHEON training tool and the collaborating external/3rd party Disaster Risk Management platforms are also given, while the deliverable is completed with the concluding remarks.

1 INTRODUCTION

According to the United Nations Office for Disaster Risk Reduction (UNDRR), "Disaster Risk Management (DRM) is the application of disaster risk reduction policies and strategies to prevent new disaster risk, reduce existing disaster risk, and manage residual risk, contributing to the strengthening of resilience and reduction of disaster losses"[3]. In the process of DRM, it is of critical importance to utilize advanced digital technologies to enhance the prevention and preparedness, to assist in the pre-disaster decision-making and post-disaster procedures, to minimize the impacts and maximize the relief measures. Moreover, taking into account the specific characteristics of the affected communities, while utilizing their individual advantages and incorporating them into the process, can create an optimized DRM and contribute to the community's resilience.

In that sense, PANTHEON envisages to address the Community-Based DRM process, by implementing a Digital Twin (DT) platform for decision-making and action planning, exploiting advanced technologies, such as Smart City sensing, Internet of Things (IoT), remote aerial and space-based sensing and Artificial Intelligence (AI). Therefore, the objective of this deliverable is to provide the design and analysis of the Smart City Digital Twin (SCDT) conceptual model, upon which the general PANTHEON architecture and relevant technologies will be founded and developed.

The document is divided into ten main sections, describing the general and specific technologies that will be used and/or implemented in the course of the SCDT development. These sections can be summarized as:

- **Section 2 – Smart City Concept:** This section presents the concept of the Smart City and its components, as it constitutes one of the foundational technologies for the development of the PANTHEON SCDT. A distinct sub-section is dedicated to smart cities for community-based disaster risk management.
- **Section 3 – Digital Twins:** The technology of Digital Twins is presented and analyzed, to assist the further understanding of the PANTHEON developments regarding the exploitation of DTs in the implementation of the SCDT model and the general PANTHEON platform architecture.
- **Section 4 – Smart City Digital Twin General Architecture:** The section presents the designed SCDT and analyses its general concept, along with its individual constituent components. It also provides information about the future development of the SCDT and concepts regarding its operation and maintenance.
- **Section 5 – Monitoring Techniques, Sensors and Data:** A detailed description of the monitoring and sensing technologies, sources and techniques that will be utilized is included in this section. These technologies and sources will provide the necessary data and information to be used for the implementation of the DT and the execution of the AI-based simulations.
- **Section 6 – Data Aggregation, Analysis and Processing:** This section focuses on the detailed big data aggregation process, analysis and processing. Since the DT will be fed by a significant amount of data, coming from a multiplicity of sources and sensors, big data analysis and techniques must take place for the proper gathering/aggregation of the data and their subsequent analysis and processing to be usable and exploitable from the DT and the simulations.

[3] https://www.undrr.org/terminology/disaster-risk-management#:~:text=Disaster%20risk%20management%20is%20the,and%20reduction%20of%20disaster%20losses.

- **Section 7 – Machine-Learning Supported Simulations:** One of the most critical SCDT components is described in this section. The performed simulations will consider all the available data and information provided into the DT and execute disaster scenario Machine Learning (ML)-supported simulations to produce results with regards to the impacts of a disaster in a specific area and community, including graphs and 3D models of the area under consideration.
- **Section 8 – AI-based Decision Support System:** The analysis of the Decision Support System (DSS) component of the SCDT is presented in this section. Assisted by an AI engine, the DSS will take as input the outputs of the simulations and produce recommendations regarding the optimum management approach to a predicted disaster scenario. Furthermore, the DSS will provide resources management and support operations and planning.
- **Section 9 – SCDT Platform User Interface:** This section presents the User Interface of the SCDT, which will include all the relevant information, graphics, 2D/3D and DT representations that are available, assisting the decision makers, stakeholders and responsible disaster management agencies in their tasks and duties, while offering them a fully digital representation of the disaster scenario, actions, the disaster struck area, etc.
- **Section 10 – 2D Virtual Representation Training Tool:** The tool analyzed in this section will constitute the training tool for the first responders and any other relevant stakeholders. A thorough analysis of the tool is given, along with operational and functional characteristics.
- **Section 11 – Third-party DRM Platforms:** This section gives an analysis of the possible collaboration/interconnection of the PANTHEON platform with 3rd party DRM platforms and providers, in an effort to enhance and further optimize the decision-making process of the PANTHEON DRM platform. Both technical and operational features are provided.

Concluding this introductory section, the following sections of the deliverable will thoroughly present and analyze the components of the SCDT, which will constitute the foundation for the further developments with respect to the PANTHEON DRM platform.

2. SMART CITY CONCEPT

2.1 SMART CITY GENERAL DESCRIPTION

2.1.1 HISTORICAL PERSPECTIVE

The concept of Smart City has become more and more popular as technology rapidly evolves over the last 20 years. Cities are regarded as pivotal components for the future, as they play a fundamental role in global social and economic dynamics [1]. To underscore this, it's worth noting that today, according to the United Nations Population Fund, more than half of the world's population are residents of urban areas, and the estimation is that by 2050, this percentage will rise to 68 percent [2]. As the population in urban areas continues to grow, cities have to deal with very crucial issues that come along with these major changes, such as the proper distribution of resources, increasing traffic, pollution, city crowding, and poverty. Figure 1 and Figure 2 are depicting the UN's corresponding population projections.

The exponential growth of urban population is one of the primary catalysts and as more people migrate to cities, there is an increased strain on existing transportation, housing, existing infrastructure and public services. This creates a necessity for smarter urban planning, to respond to those important factors and provide a more efficient allocation of resources and land use. Moreover, climate change and resource depletion have prompted the need for sustainable urban development. According to UN Habitat, cities consume 78% of the world's energy and produce more than 60% of greenhouse gas emissions [4]. So to avoid unsustainable practices that can lead to environmental degradation, smarter urban planning aims to reduce these negative impacts by promoting energy-efficient buildings, environmental-friendly means of transportation, and more green spaces.

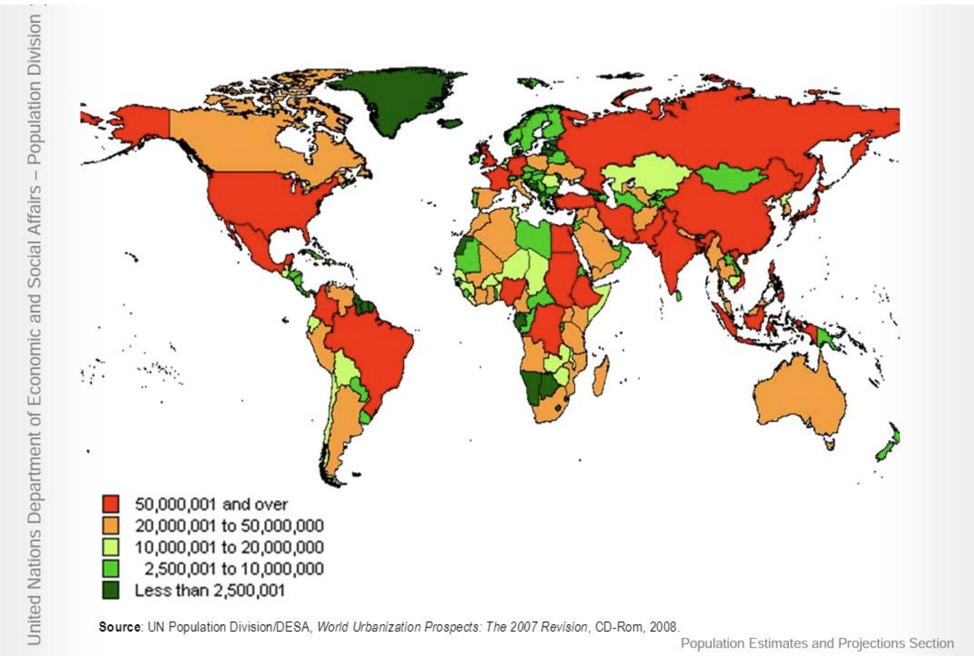

Figure 1 - Population in urban areas in 2050, [3].

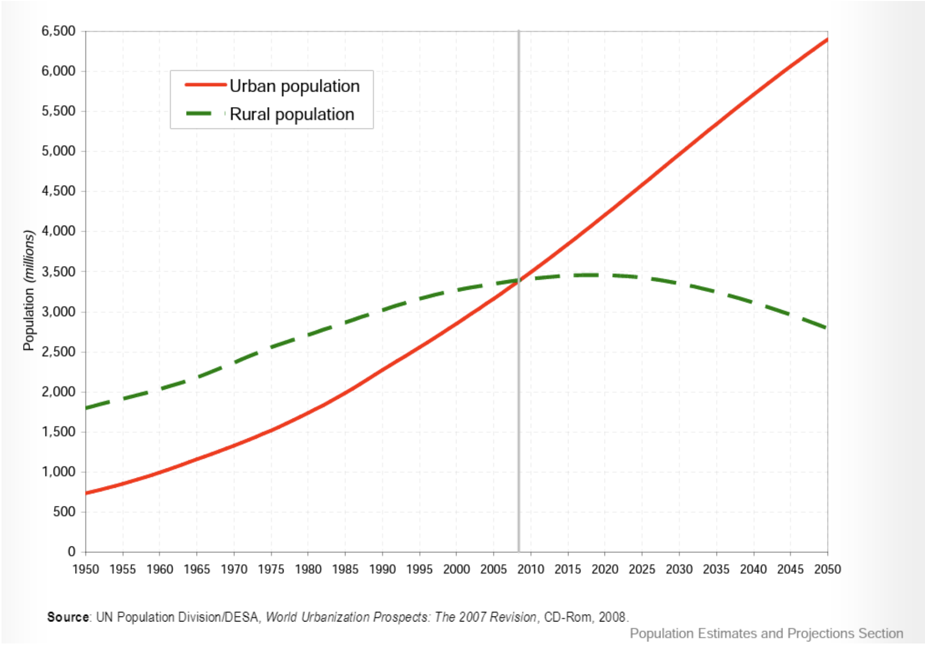

Figure 2 – Global rural and urban population (1950-2050), [3].

2.1.2 DEFINITION AND KEY CHARACTERISTICS

Today there is not an absolute definition of the term "Smart City", because it depends on the meaning and use of the word '*smart'* in each case - intelligent, knowledge, ubiquitous, sustainable, digital, green, wired [5].

A more general description of the Smart City concept could be that a smart city strategy aims to utilise science and technology through the ICT (Information and Communications Technology) to increase the quality of life in urban space, both improving the environmental quality and delivering better services to the citizens. This is graphically presented in Figure 3.

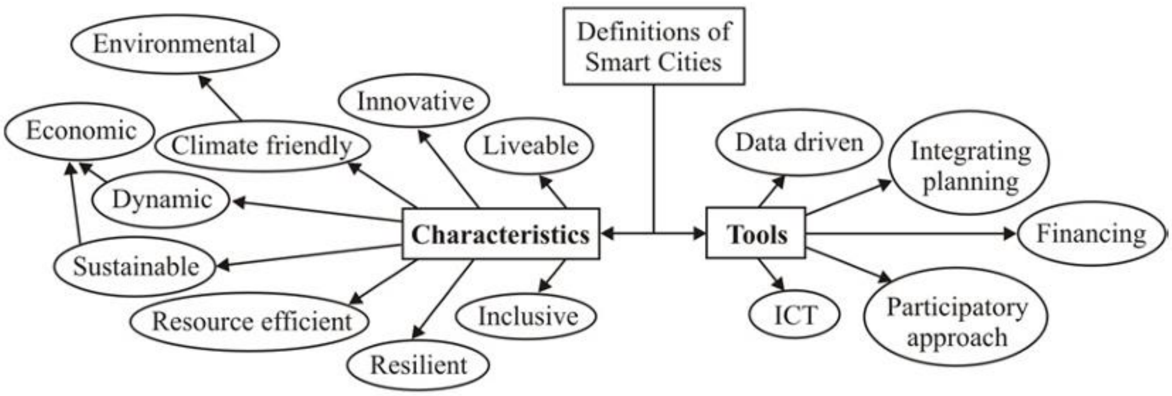

Figure 3 – Main characteristics of a smart city and its tools, [6].

A Smart City is characterised by a multifaceted transformation driven by technology, data, and sustainability. At its core, it leverages advanced digital infrastructure and the Internet of Things (IoT) to connect and optimise various aspects of urban life. In a Smart City, data collected from sensors embedded in infrastructure, public spaces, means of transportation, networks, integrated materials, and even everyday objects flows seamlessly, providing valuable insights for urban planning and management. These cities prioritise efficiency, responsiveness, and sustainability. They employ technologies to improve transportation systems, manage energy consumption, enhance public services, and ensure the well-being of their citizens. The result is a dynamic and adaptive urban environment where technology not only helps to make daily life easier but also to address pressing challenges such as congestion, pollution, and resource management. The combination of all the above, along with the contribution of STEM (Science Technology Engineering Mathematics) and more scientific fields, like biology, chemistry could lead to a self-monitoring mechanism [7]. A depiction of the most basic smart city components is presented in Figure 4.

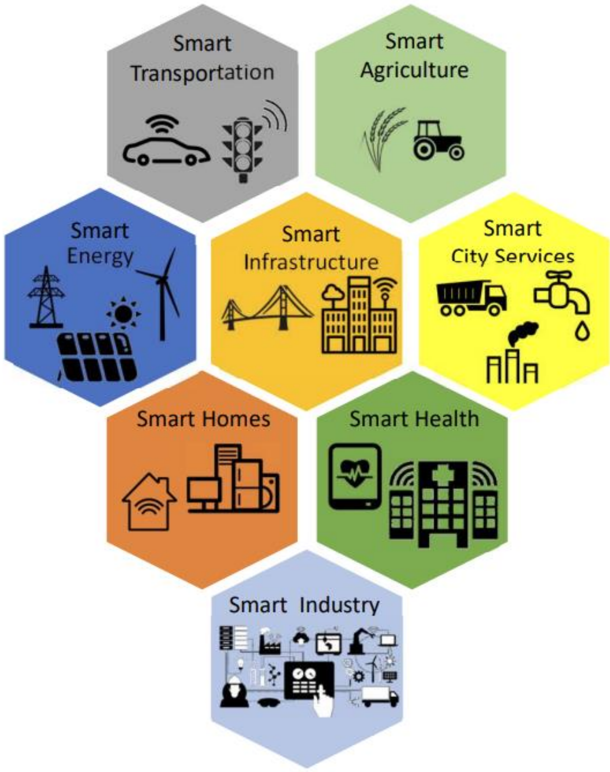

Figure 4 – Smart City components, [8].

2.1.3 TECHNOLOGICAL INTEGRATION

Utilising the possibilities of the Internet of Things (IoT) to harvest data and generate Big Data, which then will be used by Artificial Intelligence (AI) and Machine Learning (ML), can provide accurate estimations and create more suggestions and sustainable solutions and environments for the city. Data-driven algorithms reading all that provided data can provide decisions and solutions that will be citizen-oriented and will focus on the improvement of the citizen's liveability. Data analytics will also provide a better understanding about the city's needs, evolution, adaptation and allow the city authorities to have a fast response time to various situations and conditions [9].

To be able to achieve this functionality, many resources must be available and when combined, they can be used to extract and provide data, to perform all the above actions. Those resources could include: Sensors for monitoring the water quality, light, rain, temperature, air humidity, soil humidity, wind speed, pressure, solar radiation, air quality, smoke detection, gas concentration, infrared radiation, motion sensors. Mobile phones, weather stations, microclimate stations, smart traffic lights, Wi-Fi networks, 3/4/5G technologies, cloud storage services, smart grids for providing more information about the power generation, GPS could also be used as a data source for the real-time AI algorithms [9, 10]. The basic IoT architecture is shown in Figure 5, while the various sensing technologies and applications are presented in Figure 6.

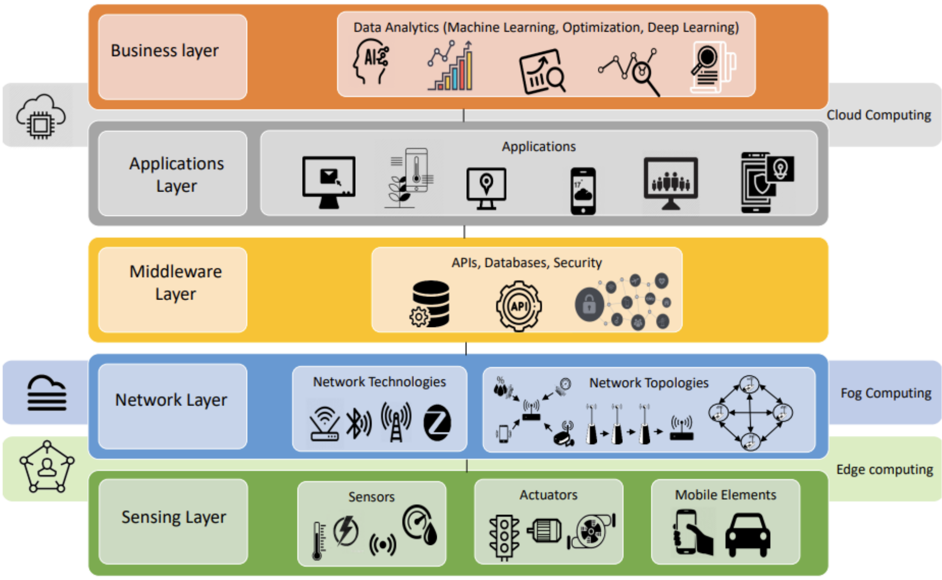

Figure 5 – IoT Architecture, [8].

Figure 6 – Sensing Technologies for IoT Smart Cities, [8].

2.1.4 URBAN MOBILITY

Urban Mobility is a critical component of smart cities, addressing the challenges associated with the movement of people and goods in increasingly densely populated urban areas. The concept of urban mobility within a smart city framework involves the deployment of innovative technologies to create efficient, sustainable, and inclusive transportation systems. These systems are designed to reduce traffic congestion, lower pollution levels, and improve overall accessibility. Smart cities leverage real-time data and improve traffic management solutions to optimise transportation routes, enhance public transit services, create various alternative routes (in case of traffic or emergencies) and provide residents with a range of convenient and eco-friendly mobility choices [11], as shown in Figure 7.

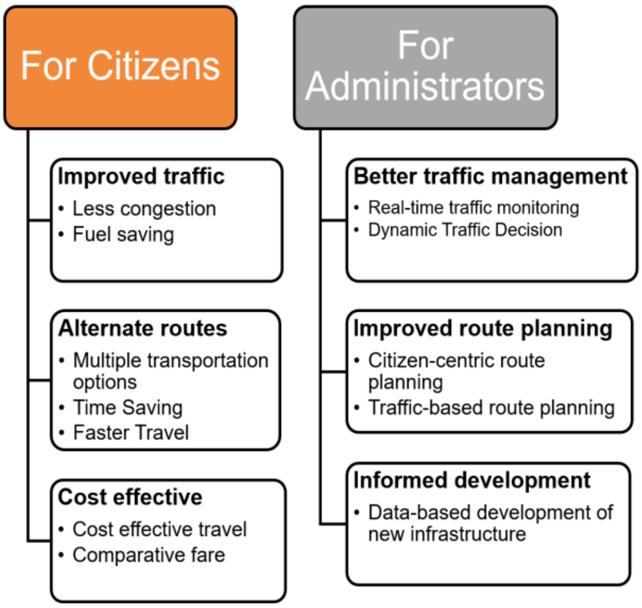

Figure 7 – Need and importance of smart mobility, [11].

2.1.5 PUBLIC SERVICES AND GOVERNANCE

Public Services and Governance in smart cities mark a transformation in the way urban centres deliver services and engage with their residents. These cities leverage technology to streamline service delivery, optimising healthcare, education, disaster management, waste management, and more through data analytics, predictive maintenance, and automation. E-Governance, offering digital platforms, mobile apps, and online portals that empower citizens to access government services, report issues, and actively participate in decision-making. Transparency and accessibility are hallmarks of this approach. Moreover, citizen engagement is a central theme, with residents encouraged to provide feedback and contribute to local governance through open data portals, public consultations, and crowd-sourced urban planning. Data-driven policy making, using real-time information to inform decisions, plays a pivotal role. For instance, data informs traffic management decisions to improve transportation systems. Challenges such as data privacy and security are addressed, and success stories from various cities provide insight into how data-driven governance and inclusive public service delivery are transforming urban life, bridging the digital divide and fostering a more equitable and responsive urban environment [12].

2.2 SMART CITIES FOR COMMUNITY-BASED DISASTER MANAGEMENT

A smart city is an urban environment that leverages advanced technologies, including information and communication technologies (ICT), the Internet of Things (IoT), data analytics, and artificial intelligence, to enhance the efficiency, sustainability, and quality of life for its residents. Smart cities integrate interconnected digital infrastructure to collect, process, and analyze data from various sources, such as sensors, devices, and citizens, in real-time.

Community-Based Disaster Management (CBDM) is an approach to disaster preparedness, response, and recovery that places the community at the center of these efforts. It emphasizes the active involvement, participation, and empowerment of local communities in planning, coordinating, and implementing disaster risk reduction and management strategies. CBDM recognizes that communities are often the first responders during disasters and possess valuable knowledge about their vulnerabilities, resources, and needs.

PANTHEON project aims to establish a Community-based Digital Ecosystem utilizing Smart Cities technology and sophisticated interdependent visual and data analytics. It is designed to facilitate human-infrastructure technology interactions, thereby achieving urban sustainability and resilience objectives. Includes the analysis of Community-Based Disaster Risk Management (CBDRM) and Disaster Risk Reduction (DRR) national and regional policies, planning, priorities, as well as the legal and regulatory environment.

Existing tools and decision-making systems for community-based Disaster Risk Management (DRM), encompassing human, technical, material, and financial resources can be used. Through participatory actions, the initiative will conduct a comprehensive analysis involving regional Multi-Hazards/risk data and assessment, and community vulnerability and capacity assessments. The overarching goal is to design and develop a community-based SCDT that effectively supports community disaster management and enhances situational awareness.

The primary outcomes of the platform will include risk assessment to prevent and mitigate the impact of disasters, identification of vulnerable regions based on local disaster models, dissemination of information to raise societal awareness about disaster hazards and risks, and improvement of disaster management capacity and capability.

To ensure a comprehensive and inclusive approach, participatory processes will be applied, involving representatives from all sections of the community and sources of expertise. A key component of this initiative is the establishment of a participatory governance model, with a special focus on keeping vulnerable groups informed and involved in the decision-making process.

Living in a secure and resilient smart city, equipped with a Smart City Critical Infrastructure (SCCI), offers citizens the assurance of uninterrupted access to essential services, ranging from public transportation and communication networks to energy and water distribution, hospitals, and educational institutions. The components of these critical infrastructures encompass gas stations, power plants, healthcare facilities, transportation systems, financial institutions, government offices, military installations, water reservoirs, bridges, and more. The smooth operation of these critical infrastructures is paramount to the well-being of urban populations. Disruptions in the operational continuity of the SCCI can result from various sources, including natural disasters or human-made hazards, including physical and cyber-attacks. Recent reports and publications underscore a growing trend of combined physical and cyber-attacks that can lead to cascading effects within the SCCI network due to interdependencies among critical infrastructures.

Protecting cities from the potential failures and disruptions of their critical infrastructure has become an increasingly complex challenge. It necessitates a multidisciplinary approach, bringing together a diverse range of skills, from security and maintenance to communication, transportation planning, anthropology, social science, energy network management, hospital services, IT, research, and threat intelligence, among others. Additionally, it requires the ability to correlate and analyze vast volumes of data and information from multiple sources, including social media. To safeguard a complex urban environment, it's crucial to acknowledge the intricate interplay between different types of critical infrastructure and to develop tools and methods capable of minimizing cascading effects and enabling rapid recovery of service performance levels after disruptions. This represents a fundamental aspect in preserving the livability of the urban environment.

2.2.1 COMMUNITY-EMPOWERMENT

While disasters have the potential to affect wide regions or entire nations, their impact is most acutely felt at the community level, often striking one or several communities simultaneously. These communities collectively constitute what is commonly referred to as 'disaster fronts'. Positioned at the forefront, communities must possess the capability to independently respond to threats. Consequently, it becomes imperative for communities to actively engage in managing the risks that pose a threat to their well-being.

Although various community empowerment programs related to disaster mitigation have successfully achieved their objectives, they frequently exhibit a short-term focus, with issues of sustainability seldom receiving adequate attention. Governmental, non-governmental, and international organizations implement diverse programs both before and after disasters, achieving notable success during the project period. However, these achievements tend to diminish gradually over the years. The lack of effective participation and capacity building within local communities to sustain these programs emerges as a significant factor contributing to their lack of enduring impact.

Recognizing that governments bear the primary responsibility for disaster management, it is essential to acknowledge the roles played by different stakeholders. Historically, top-down and command-and-control approaches were commonly employed to manage the aftermath of disasters. In this hierarchical approach, decisions were dictated by higher authorities based on their perception of needs, relegating communities to the role of mere 'victims' or recipients of aid. However, this approach has proven ineffective in practice, failing to meet critical humanitarian needs, necessitating excessive external resources, and resulting in overall dissatisfaction despite extraordinary management measures. This failure stems from the community, as the primary stakeholder directly impacted by disasters, being excluded from the decision-making and implementation processes.

Conversely, leaving communities to cope with disasters in isolation presents its own challenges. Many developing and underdeveloped countries, in particular, witness the disproportionate impact on the poor, who lack sufficient survival resources and access to adequate infrastructure and social services.

Empowering communities for disaster risk management entails their active participation in risk assessment, mitigation planning, capacity building, involvement in implementation, and the establishment of monitoring systems that secure their stake in the process.

2.2.2 INTEGRATING COMMUNITY-BASED DISASTER MANAGEMENT (CBDM) IN SMART CITIES

Implementing Community-Based Disaster Management (CBDM) in smart cities involves integrating community-driven disaster preparedness, response, and recovery strategies into the broader framework of a technologically advanced urban environment. The process requires/should include the following steps:

1. Community Engagement and Participation:

- Smart cities should actively engage with local communities through digital platforms, mobile apps, and social media to facilitate participation in disaster management planning and decision-making.

- Utilize technology to conduct virtual town hall meetings, webinars, and forums to involve community members in identifying vulnerabilities, assessing risks, and developing disaster preparedness plans.

2. Early Warning Systems:

- Develop and deploy advanced early warning systems that provide real-time information about impending disasters, such as severe weather, earthquakes, or flooding.

- Ensure these systems are accessible to all community members through multiple communication channels, including smartphone apps, text messages, and social media.

3. Crowdsourced Data:

- Encourage citizens to contribute data about disaster impacts, such as road closures, infrastructure damage, and emergency shelter availability, through smartphone apps and social platforms.

- This crowdsourced information can aid emergency responders in making informed decisions and prioritizing response efforts.

4. Disaster Response Apps:

- Applications that provide disaster-specific information, guidance, and emergency contacts for residents.

- Enable two-way communication to allow residents to report their status, request assistance, and receive real-time updates from local authorities.

5. Resilient Infrastructure:

- Design smart city infrastructure, such as transportation networks and public buildings, to withstand disasters, ensuring that critical facilities are easily accessible to residents during emergencies.

- Employ technologies like sensors and remote monitoring to assess infrastructure integrity and safety in real-time.

6. Community Resilience Hubs:

- Establish community centers equipped with smart technologies that can serve as hubs for disaster response and recovery efforts.

- These hubs can provide resources, shelter, communication facilities, and access to critical services during disasters.

7. Data Analytics:

- Utilize data analytics and machine learning to process and analyze vast amounts of data, such as social media feeds and sensor information, to better understand disaster impacts and community needs.

- This data-driven approach can help authorities make informed decisions and allocate resources effectively.

8. Education and Training:

- Develop online and interactive training programs for community members to enhance their disaster preparedness and response skills.

- Smart cities can use e-learning platforms and virtual simulations to educate residents.

9. Collaboration and Communication:

- Facilitate collaboration among smart city stakeholders, including government agencies, non-profit organizations, businesses, and community groups, to coordinate disaster response and recovery efforts.

- Employ digital platforms to streamline communication and information sharing among these entities.

10. Post-Disaster Recovery:

- Use smart city technologies to accelerate recovery efforts by efficiently assessing damage, managing resources, and providing assistance to affected communities.

- Employ data analytics and real-time monitoring to track progress and adapt recovery strategies.

Smart cities for community-based disaster management epitomize the fusion of physical and IT systems and infrastructure, fostering social cohesion and enabling innovation and cognitive enhancement. These characteristics are harmoniously aligned with the evolving concept of resilience for cities, which is reshaping the paradigm of smart cities. Resilience in this context is the city's ability to thrive as a hub of human habitation, productivity, and cultural advancement, despite challenges posed by factors such as climate change, population growth, and globalization. Resilient cities can absorb shocks, whether from physical attacks or other disruptions, and continue their regular activities, encompassing people, goods, and services. Resilience is defined by four primary competencies: (1) Plan/Prepare, (2) Absorb, (3) Recover and (4) Adapt. These competencies should address four core socio-technical dimensions of every city: physical, information, cognitive and social.

Figure 8 illustrates an iterative model of community disaster management. The cycle encompasses response, recovery, mitigation, and preparation phases. During the response and recovery stages, data collection is employed to assess existing community conditions, generating images for use in mental or formal simulation models. These models then forecast potential outcomes based on different decisions, leading to actions and subsequent changes in community conditions. Successive cycles adapt to evolving disaster experiences and changing community conditions.

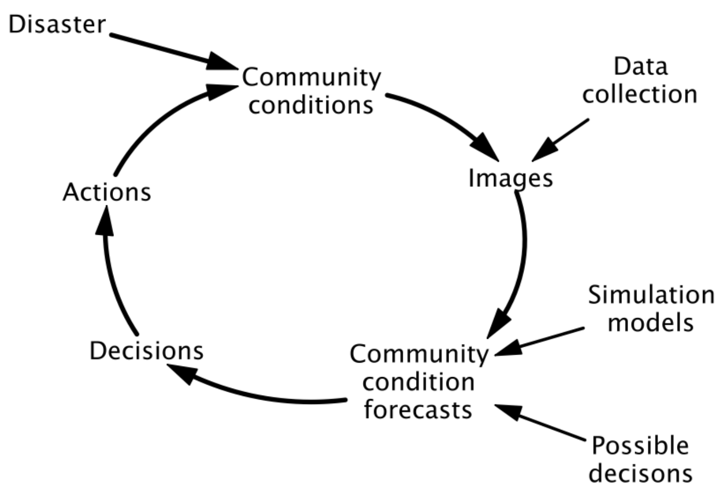

Figure 8 – A feedback model of iterative community disaster management, [13].

In the mitigation phase, System Dynamics-based Computational Thinking (SDCT) proves instrumental. It aids in evaluating alternative policies and plans to minimize loss of life and property, guiding leaders in disaster management investment decisions. In the preparation phase, SDCT facilitates the collection and analysis of near-real-time data on community and disaster event conditions, forming the basis for proactive measures such as evacuations.

During the response phase, SDCT becomes a valuable tool for reporting damage and threats to lives, enhancing the deployment of first responders. In the recovery phase, SDCT helps identify rebuilding bottlenecks and offers effective strategies for building back better. Additionally, it guides resource allocation strategies. Crucially, the depicted disaster management cycle in Figure 8 is not a finite process; it iterates until the desired end state of community conditions is achieved.

In 2020 Ford and Wolf ([13]) proposed a conceptual model for SCDT systems to effectively support community disaster management (Figure 9). The model depicts the essential elements for disaster management through continuous SCDT monitoring of community conditions. It emphasizes the iterative nature of disaster management, with SCDT consistently monitoring decision and action impacts in the digital twin. The model comprises three main parts: (i) components external to SCDT, (ii) smart city components, and (iii) digital twin components. External components link SCDT to the community and disaster events, incorporating conditions, features, and lessons learned. Smart city components include real-time data from sensors for decision-making and community presentation. Digital twin components involve tools generating digital images and simulation models for predicting future conditions. Information loops within the model support iterative, data-driven decision-making during disaster management.

SCDT enhances the speed and efficacy of disaster management by providing real-time data, forecasting, and monitoring impacts beyond manual human capabilities. This model has the potential to improve disaster management, bolster community resilience, and aid decision-makers in responding effectively to disasters. However, implementing SCDT requires addressing challenges such as integrating diverse community infrastructures and securing sufficient technology and funding support.

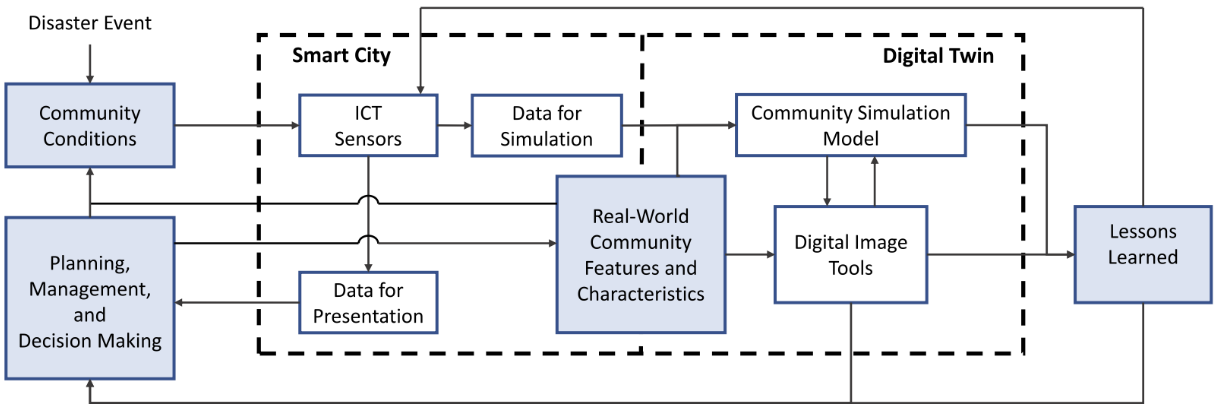

Figure 9 – Community disaster management model with a SCDT, [13].

The PANTHEON project, by integrating CBDRM into the fabric of smart cities, will support the corresponding communities to harness the power of technology and enhance disaster resilience, ensure the safety of residents, and foster a collaborative approach to disaster management. This approach recognizes the importance of local knowledge and community-driven solutions while leveraging the capabilities of a smart city's digital infrastructure.

3. DIGITAL TWINS

A digital twin is a virtual representation, a digital replica, of a physical object, process, system or place that serves as the effectively indistinguishable digital counterpart of it for practical purposes, such as simulation, integration, testing, monitoring, and maintenance. It is a dynamic and interactive model that mimics the behavior and characteristics of its physical counterpart in real-time.

Digital twins are created using a variety of data sources, including sensors, historical data, and computer simulations, and often associated with the Internet of Things (IoT) that allows the monitoring, analysis, and optimization of the corresponding real-world entity using data-driven insights.

3.1 HISTORY OF DIGITAL TWINS

The concept of digital twins can be traced back to the early days of computing.

Industries, especially aerospace and automotive, used simulations and modeling to predict how systems would behave. Computer-aided design (CAD) systems in the latter half of the 20th century allowed engineers to create digital representations of physical objects. In the 1960s, NASA developed a system called the Apollo Guidance Computer (AGC) to help astronauts navigate to the moon. The AGC ground-based systems to mirror and predict the health and performance of the Apollo spacecraft. This allowed them to simulate scenarios, test solutions, and diagnose issues in a virtual environment before transmitting solutions to the actual spacecraft.

In the 1990s, computer scientist David Gelernter published a book called Mirror Worlds, which described a vision of a future where the physical world would be mirrored by a digital world. Gelernter's book is considered to be one of the first works to describe the concept of digital twins.

The term "digital twin" was first coined in 2002 by Michael Grieves, a professor of mechanical engineering at the University of Michigan. Grieves defined a digital twin as "a virtual representation of a physical product or system that is created and maintained using data from the physical product or system."

In 2010, NASA adopted the term "digital twin" to describe its efforts to develop virtual models of its spacecraft. NASA's digital twins are used to monitor the condition of spacecraft in real-time and to predict when maintenance is needed.

With the 21st-century surge in IoT devices and Big Data analytics, the potential for digital twins grew exponentially. Suddenly, sensors could feed real-time data from physical assets to their digital counterparts, allowing for dynamic updates, real-time monitoring, and predictive maintenance. The evolution of cloud computing also made it feasible to manage vast amounts of data and run complex simulations.

The concept of digital twins has gained widespread attention as companies in a variety of industries have begun to explore the potential benefits of this technology. Digital twins are now being used to improve the design, development, operation, and maintenance of physical objects, processes, and systems in a wide range of industries, including manufacturing, healthcare, transportation, and energy. With industries recognizing the value of digital twins, the concept has expanded beyond manufacturing and aerospace to fields like healthcare, urban planning (digital twins of cities), energy and industrial components.

The most recent advancements in the digital twin arena involve the integration of artificial intelligence (AI) and machine learning (ML). These technologies enable digital twins to not just passively represent their physical counterparts but to also learn from data, predict outcomes, and even autonomously optimize processes.

3.2 TYPES OF DIGITAL TWINS

In this document the focus is on the four key categories of digital twins, namely: Component twins, Asset twins, System twins, and Process twins (Figure 10).

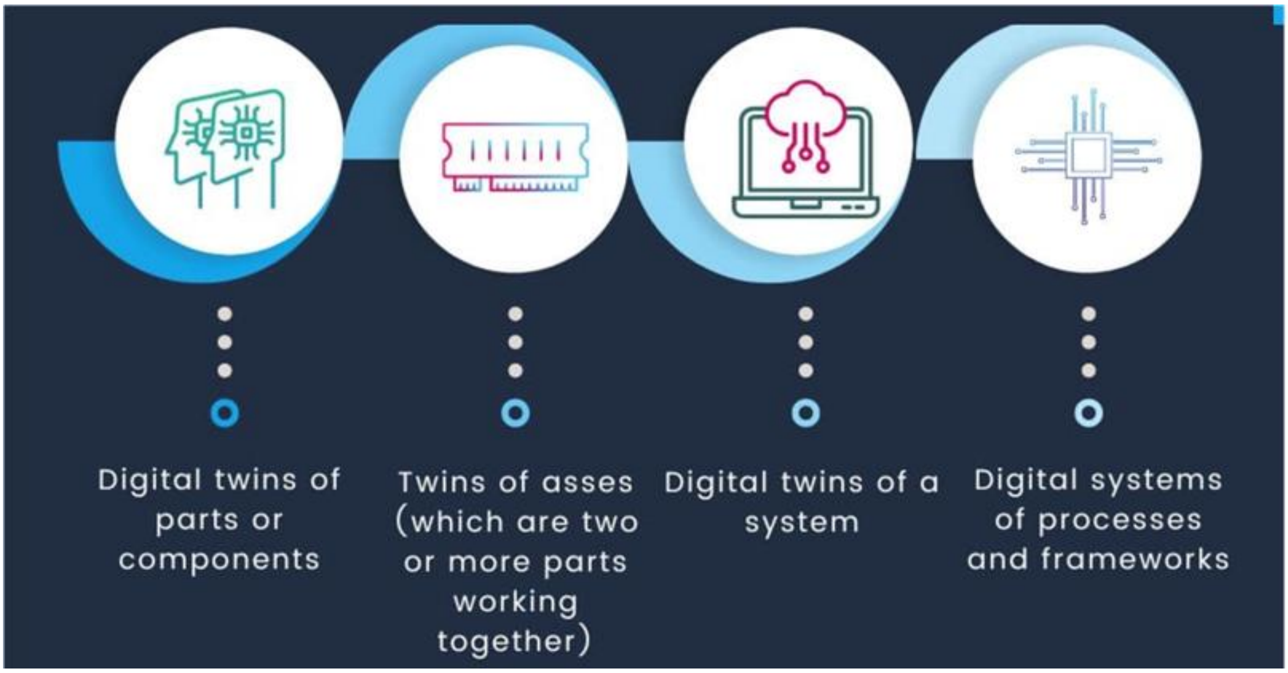

Figure 10 – Types of digital twins.

3.2.1 ASSET TWINS (PANTHEON PROJECT)

Asset Digital twin is the one that will be built on PANTHEON Project. Asset twins create a digital replica of an entire physical asset. This could be anything from an individual machine in a factory to a complete building, or even larger structures like a wind farm or oil rig, even whole cities (As PANTHEON project will do). Asset twins aggregate the data from component twins, offering a comprehensive picture of the asset's current status and performance.

Asset twins enable businesses to monitor, simulate, and optimize their assets in real-time. For instance, an asset twin of a wind turbine could analyze performance under various weather conditions, optimizing its operations to maximize energy output and minimize wear. Additionally, it could be used to predict potential failures, allowing for preemptive repairs and reducing downtime.

Asset digital twins are a cutting-edge technological innovation that revolutionizes the way we interact with physical assets. They serve as a dynamic and intricately detailed digital replica of various physical entities, ranging from individual machines within a bustling factory to expansive structures like entire buildings or even more colossal installations such as wind farms and oil rigs. Remarkably, asset digital twins can extend their scope to encapsulate entire urban environments, exemplified by ambitious projects like the PANTHEON

Project. These digital doppelgangers harness the power of data aggregation, consolidating information gleaned from their component twins. By doing so, they provide a comprehensive and up-to-the-minute snapshot of an asset's status and performance, offering invaluable insights to businesses and organizations.

The potential of asset digital twins is boundless, enabling businesses to gain unparalleled control over their assets. Real-time monitoring, simulation, and optimization are the hallmarks of this technology. For instance, consider an asset twin of a wind turbine, which can tirelessly evaluate its performance under various weather conditions. This analysis empowers the turbine to fine-tune its operations, maximizing energy output during favorable conditions while minimizing wear and tear during inclement weather. Moreover, the asset twin can act as a crystal ball of sorts, foreseeing potential failures and issues that might otherwise result in costly downtime. This predictive capability allows for proactive maintenance and repairs, ensuring that assets are kept in peak condition and delivering optimal results. Asset digital twins offer a transformative approach to asset management, ushering in an era of efficiency, sustainability, and proactive decision-making.

3.2.2 COMPONENT TWINS

Component twins, as the name suggests, represent individual components or parts of a larger system or product. These could range from individual machine parts in a manufacturing line to software modules in a complex IT infrastructure. Each component twin contains data about the specific part it represents, including its properties, behavior, and current status.

The use of component twins enables deeper understanding and precise control over individual parts of a system. This is particularly useful in manufacturing and engineering, where the performance and health of individual components can have a significant impact on the overall system. For example, in the automotive industry, component twins of engine parts could be used to predict wear and tear, facilitating preventive maintenance.

Component digital twins serve as virtual counterparts to individual components or elements within a larger system or product. Their scope can encompass a wide array of components, ranging from discrete machine parts on a bustling manufacturing line to intricate software modules within a complex IT infrastructure. These component twins are rich repositories of data, containing detailed information about the specific part they replicate, including its inherent properties, behavior, and real-time status.

The adoption of component digital twins offers an opportunity for enhanced comprehension and meticulous control over the individual elements within a system, presenting a paradigm shift in how we manage and optimize complex processes. This is particularly invaluable in the domains of manufacturing and engineering, where the performance and well-being of individual components can exert a substantial influence on the overall system's efficiency and integrity. For instance, within the automotive industry, component twins of engine parts can be harnessed to predict wear and tear with a high degree of accuracy. This predictive capability is instrumental in facilitating preventive maintenance measures, thereby averting unexpected breakdowns, increasing the longevity of the components, and ultimately optimizing the reliability and performance of the entire system. Component digital twins epitomize precision and insight, empowering industries to proactively address issues, minimize downtime, and improve the overall quality and dependability of their products and processes.

3.2.3 SYSTEM TWINS

A system twin is a comprehensive digital replica of an entire system, which can consist of multiple interconnected assets and components. This might include an entire production line in a factory, a transportation network, or a city's energy grid. System twins allow for the monitoring and simulation of complex, large-scale systems, providing insights into how different parts interact and impact one another.

System twins offer significant benefits in terms of optimizing system performance, identifying bottlenecks, and planning for changes or expansions. For example, a system twin of a city's transportation network could be used to analyze traffic flow, identify congestion points and simulate the impact of proposed changes, such as adding a new bus route or building a new road.

A system digital twin is a remarkable advancement in the realm of digital representation, as it constitutes a comprehensive and intricate emulation of an entire system. These systems may encompass a web of interconnected assets and components, creating a holistic reflection of their collective functionality. Such system digital twins have the capacity to encapsulate diverse domains, ranging from a complete production line within a factory to the intricate tapestry of a transportation network or even the intricate web of a city's energy grid. Within these digital replicas, every element is harmoniously integrated, allowing for the simultaneous monitoring and simulation of multifaceted, large-scale systems. This, in turn, unlocks profound insights into the dynamic relationships between different parts and their mutual influence.

The utility of system digital twins is profound, offering a treasure trove of advantages for businesses and organizations. They play a pivotal role in optimizing the performance of intricate systems, uncovering bottlenecks, and facilitating strategic planning for changes or expansions. For instance, consider a system twin of a city's transportation network; it stands ready to delve into the complexities of traffic flow, adeptly identifying congestion points and offering the capacity to simulate the consequences of proposed alterations. Whether it's offsetting up a new bus route or constructing of a new road, a system twin provides a virtual sandbox in which to test and evaluate these changes before implementing them in the real world. This gives decision-makers tools to support informed choices, enhance system efficiency, and ensure the seamless functioning of intricate, interconnected systems. System digital twins, thus, represent a transformative tool for system optimization and strategic planning across a multitude of industries.

3.2.4 PROCESS TWINS

In contrast to the previous categories that primarily focus on digital representations of physical entities, process twins offer a unique perspective by creating a virtual mirror of a business process or operation. These process twins span a wide spectrum, encompassing various aspects such as manufacturing processes, supply chain operations, customer service workflows, and even the intricate phases of a software development lifecycle. Process twins are designed to provide businesses with an in-depth comprehension of how these processes function, their level of efficiency, and the bottlenecks that may impede their smooth execution.

Process twins offer real-time monitoring capabilities, which empower organizations to swiftly pinpoint and address any issues that may arise during the process. Furthermore, they extend their utility by enabling businesses to simulate and assess potential changes or improvements to a process, all without the need for costly or risky real-world implementation.

To illustrate, consider a process twin of a supply chain operation, a critical component for businesses that rely on timely and efficient movement of goods. This process twin serves as an invaluable tool for monitoring the flow of products, identifying bottlenecks or delays in the supply chain, and even predicting the potential impacts of disruptions, whether caused by extreme weather events or fluctuations in demand. Armed with such insights, businesses can meticulously fine-tune their processes, striving for optimization and cost reduction. The ability to enhance efficiency and adapt swiftly to unforeseen circumstances not only benefits the organization's bottom line but also translates into improved service and satisfaction for their customers. Process twins, therefore, represent an innovative solution for businesses to fine-tune their operations, increase their agility, and deliver superior service in an ever-evolving business landscape.

3.3 DEVELOPING A SMART CITY DIGITAL TWIN (SCDT)

A Smart City Digital Twin (SCDT) is an advanced application of the Digital Twin concept to model and simulate the entire urban environment of a Smart City. It encompasses not only physical assets like buildings and infrastructure but also includes social and environmental aspects, such as citizen behavior, air quality and traffic patterns. By combining real-time data, historical data and advanced simulation techniques, a SCDT enables city planners and policy makers to make data-driven decisions for urban planning, management and service optimisation. It plays a crucial role in revolutionizing urban governance and transforming cities into more efficient and sustainable environments. (D3.1 - PANTHEON Technology Roadmap for Disaster Resilient Communities)

Creating a SCDT involves a combination of data collection, modeling, and integration of the right software and hardware tools.

1. Hardware Design:

- **Sensors**: Install the necessary sensors on the physical asset to collect real-time data. This could include temperature sensors, pressure sensors, cameras, accelerometers, etc.
- **Connectivity**: Ensure there's a way for the sensors to send data to a centralized system, typically using wired or wireless communication protocols suitable for your environment.

2. Data Collection and Integration:

- **Data Collection**: Begin collecting data from the physical asset through the sensors.
- **Data Integration**: Combine this data with other relevant information, such as historical data, design data, or any other pertinent datasets.

3. Digital Model:

- **Physical Model**: Start by creating a virtual representation of the asset. This could be a 3D model, a system diagram, or any other appropriate visualization.
- **Data Mapping**: Overlay real-time and historical data onto this model. For example, if you're monitoring a machine, show real-time temperature or vibration levels at relevant parts of the model.

4. Choose or Develop the Right Software:

- **Simulation Software**: Depending on your industry, there might be existing software solutions tailored for creating digital twins.

- **Custom Development**: In some cases, you might need to develop custom software solutions, especially if you have unique requirements. 6. Implement Data Analytics:
- **Descriptive Analysis**: Understand the current state of the asset by analyzing real-time data.
- **Predictive Analysis**: Use historical data to predict future behavior or potential issues.
- **Prescriptive Analysis**: Go beyond prediction to recommend specific actions based on the data.

5. User Interface (UI):

- **Visualization**: Create a UI that allows users to interact with the digital twin, visualize real-time data, and understand analytics results.
- **Interaction**: Depending on your objectives, users might need tools to run simulations, adjust parameters, or input new data.

6. Integration and Communication:

- **Feedback Loop**: Ensure there's a system in place for the digital twin to communicate insights back to operators or even directly to the physical asset (for automation purposes).
- **APIs and Integration**: If you're using multiple software solutions, ensure they can communicate seamlessly. This often involves integrating through APIs.

7. Test, Refine, and Iterate:

- **Validation**: Initially, run the digital twin in parallel with the physical asset to validate its accuracy.
- **Refinement**: Based on discrepancies or insights, refine the model, analytics algorithms, or any other aspect of the digital twin.
- **Iteration**: Continuously improve and update the digital twin as more data becomes available or as the physical asset undergoes changes.

7. Scale and Maintenance:

- **Scale**: Once the digital twin model works for one asset, you might scale it to cover multiple assets or integrate it deeper into organizational processes.
- **Maintenance**: Ensure regular software updates, calibration of sensors, and validation of the twin's accuracy.

3.4 DIGITAL TWINS FOR DISASTER MANAGEMENT IN SMART CITIES

Digital twins are virtual representations of physical objects, processes, or systems. They are created and maintained using data from the physical counterpart, and they can be used to simulate the behavior and performance of the physical counterpart in real-time.

Digital twins have the potential to play a significant role in disaster management in smart cities. By providing real-time information about the city and its inhabitants, digital twins can help city planners and emergency responders to make better decisions about how to prevent, prepare for, respond to, and recover from disasters.

Integrating a digital twin into a smart city's disaster management system can significantly enhance the city's resilience and responsiveness. It provides a holistic, data-driven approach to understanding potential threats, mitigating risks, and recovering post-disaster. As technology continues to evolve, the potential for digital twins in this arena will only grow, making cities safer and more adaptable in the face of natural or man-made disasters.

PANTHEON project aims to utilize digital twins in Athens and Vienna to be used for disaster management of:

- Earthquakes
- Floods
- Wildfires
- Heatwaves
- Technology hazards
- Terrorism

In addition, SCDT can be used to support disaster management to:

- Identify potential risks from natural disasters. This information can be used to develop mitigation plans and to prepare for disasters.
- Develop evacuation plans that take into account the needs of different populations and the potential impact of different disaster scenarios.
- Coordinate relief efforts by providing real-time information about the needs of people who have been affected by a disaster and the location of resources.
- Assess the damage caused by a disaster. This information can be used to plan for recovery and to allocate resources.

Overall, digital twins have the potential to revolutionize disaster management in smart cities. By providing real-time information and insights, digital twins can help city planners and emergency responders to make better decisions about how to prevent, prepare for, respond to, and recover from disasters.

4. SMART CITY DIGITAL TWIN GENERAL ARCHITECTURE

4.1 SCDT GENERAL CONCEPT AND ARCHITECTURE

The schematic diagram of the SCDT architecture is depicted in Figure 11. It was designed based on the characteristics and requirements of the PANTHEON DT and DRM platform, as described in the technical part of the proposal. This section will provide an overview of the SCDT constituent components and their basic functionalities and operational features.

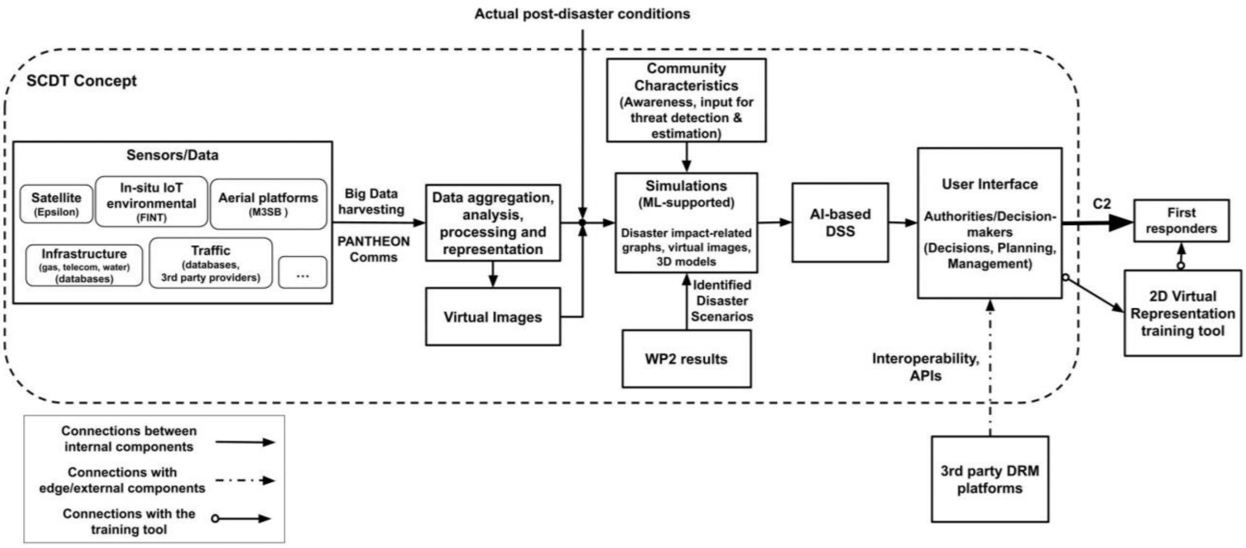

Figure 11 – SCDT conceptual model architecture.

The SCDT will constitute the basis for the PANTHEON DRM architecture and operational framework. The starting point for its development is the effective gathering of all the relevant and necessary data and information that will feed the DT and the simulation-supported decision-making process.

In that sense, the first SCDT building block is comprised of the Sensors and Data component, which includes all the data that will be gathered, along with the corresponding data sources. These data can be listed as:

- **Satellite data:** Provided by EPSILON, by utilizing the European Copernicus Earth Observation (EO) programme and its services.
- **In-situ IoT data:** Provided by FINT, by deploying its proprietary developed IoT-based weather stations, offering local weather and micro-climate parameters, such as air temperature, solar radiation, wind vector, etc., suitable for representing the local weather conditions in the area of interest and assisting in the digital reconstruction of the local environment and in the forecasting of the weather-related disasters.
- **Aerial platforms-based data:** Provided by M3SB, by deploying its fixed-wing UAV, these data will be used to reconstruct a 2-dimensional digital twin of the area of interest.
- **Infrastructure data:** These data will be provided by external and publicly available databases and repositories and will offer a picture of the public infrastructure in the area of interest.

- **Traffic data:** Historical and real-time data related to the traffic conditions in the area of interest, assisting in the better representation of the local conditions and in constructing escape plans during and/or a disaster.
- **Any other type of data,** that could assist in the digital representation and depiction of the area of interest and its living population and enhance the optimized DRM and decision-making processes, e.g., socio-economic data.

The next step is the actual acquisition of the aforementioned data, which will be achieved through the PANTHEON communications network, by also applying big data harvesting techniques, due to their big volume. Subsequently, the data will be analyzed and processed in the second building block, in order to be ready for usage in the next steps. Moreover, the first virtual images of the area of interest will be produced by the aggregated data.

One of the major SCDT blocks is the ML-supported simulations, which follows the data aggregation and analysis part. Starting from the various data storages, the aggregated and processed data, along with the produced virtual images, will be sent/fed as inputs to the DT simulation component. ML algorithm will handle the data and perform simulations regarding the disaster scenarios and the corresponding outcomes/impacts in the area of interest. It must be noted that two additional inputs will be taken into account in the simulations,: i) the identified disaster scenarios fed into the DT, and ii) the various community characteristics, including awareness, social media and public engagement, and more.

The simulation outputs, such as graphs, 3D models and virtual images, will be fed to an AI-based Decision Support System. This system, while being responsible for asset and resources management, it will be mainly utilizing AI algorithms to produce decisions about the management and actions to be taken according to the simulated disaster scenario impacts and outcomes.

Finally, the last SCDT main component is the User Interface, which will be the endpoint for the SCDT and the means for the interaction with the relevant end-users and DRM stakeholders. Specifically, the UI will mainly depict the simulation results, along with the 2D/3D representations of the area of interest. Secondly, the UI will incorporate the 2D training tool, which will be used for user training (e.g. first responders).

The decisions that will be produced by the whole SCDT operation, along with the end-users and stakeholders, will be communicated to the suitable first responders (e.g. fire fighters, civil security personnel), to prepare them for the actions to be taken in the framework of the optimized DRM process.

Furthermore, the conceptual model, as presented herein, also includes an edge/external component, which is the interconnection/collaboration with 3rd party DRM platform providers. This interconnection will offer the PANTHEON platform a more complete view and additional valuable information with respect to the area of interest and the possible/imminent disasters and their management actions and procedures.

4.2 SCDT DESIGN AND DEVELOPMENT

The PANTHEON Smart City Digital Twin needs a methodology for its design and development. In PANTHEON, the focus is on a community-based Smart City Digital Twin for Disaster Management. However, to design and develop such a system involves a systematic approach that integrates technological advancements with community characteristics and aligns with industry standards. The following design and development characteristics and recommendations based on the previously defined general concept and architecture, outline key steps in the process and are described below.

4.2.1 DEFINITION OF DISASTER MANAGEMENT REQUIREMENTS

This step involves the specific disaster management needs of the communities in the under-study regions (Greece/Attica and Austria/Vienna). This includes understanding the types of disasters prevalent in the regions, potential impacts, and community vulnerabilities. This process starts with a comprehensive understanding of the community's characteristics, vulnerabilities, and historical exposure to various disasters. Collaboration with local authorities, community leaders, and stakeholders is essential to gather valuable insights. Information on prevalent disasters, such as floods, earthquakes, or wildfires, shapes the digital twin's capabilities. Engagement with a diverse range of stakeholders is imperative to capture a holistic view of disaster management requirements. This involves local government officials, civil protection officials, first responders, community members, representatives of vulnerable group and experts in relevant fields. Stakeholder workshops, interviews, and surveys are conducted to gather diverse perspectives, ensuring the digital twin addresses the needs of all community segments. A comprehensive risk assessment follows, identifying potential scenarios and understanding the severity of disaster impacts on the community. The goal is to prioritize and categorize risks based on likelihood and potential consequences, guiding the digital twin's functionalities to address high-priority scenarios. Simultaneously, legal, and ethical considerations become integral. Privacy laws, data protection regulations, and ethical standards must be considered within the digital twin framework. Establishing clear guidelines on data ownership, consent mechanisms, and transparent communication with the community is essential to build trust and address ethical concerns. In PANTHEON, these concepts have been extensively researched in WP2 and T3.1, T3.2, while these are currently taken into consideration for active discussions happening in T3.3, T3.5 and T3.6.

4.2.2 SMART CITY STANDARDS ALIGNMENT

The PANTHEON DT design needs to align with well-established smart city standards. Organizations such as IEEE, IETF, and ETSI offer valuable guidelines. An example is IEEE P2668[4] for smart cities and communities' standards. Notably, IEEE 2413-2019 provides a foundation for structuring digital twin implementations, while ISO/IEC 30182:2021[5] offers guidelines for integrating digital twins with Building Information Modelling (BIM), a critical aspect for disaster management in urban areas. The DT could be aligned with established smart city frameworks such as ISO 37120:2018[6],, which provides indicators for city services and quality of life. Additionally, the Open & Agile Smart Cities (OASC) Minimal Interoperability Mechanisms[7] could be leveraged to promote standardization for core services in smart cities. Data interoperability could be assured by adopting standards e.g., from the Open Geospatial Consortium (OGC), such as OGC CityGML[8], facilitating the representation and exchange of 3D city models and ensuring seamless interoperability between various components of the PANTHEON DT. Regarding security standards, adhering to standards such as ISO/IEC 27001:2013[9] for information security management and applying security controls outlined in e.g., ISO/IEC

[4] https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/smart-and-sustainable-cities-and-communities-rp2023
[5] https://www.iso.org/standard/82128.html
[6] https://www.iso.org/standard/70469.html
[7] https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/smart-and-sustainable-cities-and-communities-rp2023
[8] https://www.opengeospatial.org/standards/citygml
[9] https://www.iso.org/obp/ui/#iso:std:iso-iec:27001:ed-2:v1:en

27002[10] to safeguard sensitive information within the DT should be prioritised. For example, the ISO 22324:2022[11] could be advised for guidelines on emergency management, incorporating aspects of disaster preparedness and response within the PANTHEON DT to enhance overall resilience. Also, Artificial Intelligence (AI) algorithms could be integrated within the PANTHEON DT by utilizing standards such as ISO/IEC 23053:2022[12] for the use of AI in disaster management, thus enhancing situational awareness and decision-making capabilities. Finally, guidelines, e.g., from ISO 37106:2021[13] for smart community infrastructures could be embraced, ensuring active community engagement in the development and utilization of the PANTHEON DT. This aligns with the principles of inclusivity and responsiveness, contributing to the overall success of the PANTHEON smart city disaster management system.

4.2.3 DATA COLLECTION, INTEGRATION AND MONITORING

The PANTHEON DT design involves meticulous plans for gathering and integrating data from in-situ IoT sensors, satellites, Unmanned Aerial Vehicles (UAVs), social media, and Critical Infrastructures. This critical step is fundamental to the development of a digital twin, a virtual representation mirroring the intricate details of the physical city and plays a pivotal role in ensuring the accuracy and completeness of the information it encapsulates. This includes a meticulous definition of data requirements, an essential step in articulating the types of data needed for a comprehensive digital twin, a research item of T1.5 and T3.4. This encompasses a broad spectrum, ranging from environmental factors to infrastructure details and various social parameters, all crucial for creating a holistic representation of the city. Subsequently, the identification of data sources becomes imperative, involving a cataloguing process that spans potential repositories such as IoT sensors, GIS databases, social media feeds, and Critical Infrastructure records. This exhaustive identification process ensures that no valuable data is overlooked, laying the groundwork for a thorough and encompassing dataset. Ensuring the quality of the collected data is the next logical step, involving measures for data quality assurance. This crucial process ensures the data's accuracy, completeness, and consistency, with adherence to recognized data quality frameworks such as the ISO 8000 series. Interoperability standards play a significant role in facilitating the seamless integration of heterogeneous data sources. Internet of Things (IoT) frameworks recommended by ITU-T[14] (International Telecommunication Union Telecommunication Standardization Sector) could be implemented for scalable and interoperable sensor networks. For example, the oneM2M[15] standard could be leveraged for seamless IoT device communication and data exchange. Adhering to standards like IEEE P2413[16] provides guidelines for achieving interoperability, allowing different data types to work cohesively within the PANTHEON DT. The integration of Geographic Information System (GIS) and Building Information Modelling (BIM) data emerges as a fundamental step in urban digital twin technology. This integration, highlighted in studies such as the one by Xia et al.[17], forms a basic technology for realizing smart cities. Seamless integration with the digital twin platform should be ensured, following guidelines e.g., from the Open Geospatial Consortium (OGC) on SensorThings API[18]. The

[10] https://www.iso.org/standard/75652.html
[11] https://www.iso.org/standard/84559.html
[12] https://www.iso.org/standard/74438.html
[13] https://www.iso.org/standard/62065.html
[14] https://www.itu.int/en/ITU-T/Pages/default.aspx
[15] https://www.etsi.org/committee/1419-onem2m
[16] https://standards.ieee.org/ieee/2413/6226/
[17] https://www.sciencedirect.com/science/article/pii/S2210670722003298
[18] https://www.ogc.org/standard/sensorthings/

implementation also adheres to the principles of ISO 19156:2023[19] for Observations and Measurements to standardize sensor data. For developing data collection and integration techniques, platforms like ArcGIS[20], QGIS[21] for spatial data, and open-source IoT platforms like ThingsBoard[22] could be utilised. Dynamic data streaming mechanisms are then implemented, ensuring the digital twin consistently reflects the current state of the city. This dynamic aspect empowers decision-makers with access to up-to-date information, fostering better analysis and informed decision-making. Security measures are given paramount importance, involving the application of encryption and access controls. Compliance with standards such as ISO/IEC 27001 contributes to the establishment of robust security measures, safeguarding sensitive information from unauthorized access. Establishing a data governance framework is crucial for managing the entire data lifecycle. This encompasses aspects like data access, privacy, and adherence to relevant standards, contributing to the responsible and ethical use of data. The deployment of a robust data integration platform is imperative, one capable of handling diverse datasets and compliant with standards such as those outlined by ETSI ISG CIM[23]. Creating a comprehensive metadata catalogue becomes a pivotal part of the process, documenting and managing data attributes to enhance the usability of the digital twin. Addressing ethical considerations related to data collection is the final layer of this comprehensive methodology. This involves ensuring that data collection practices align with regulations and ethical guidelines to protect the privacy and rights of individuals, such as GDPR. Finally, a user-friendly interface for real-time data visualization should be designed following principles from ISO 9241-210:2019[24] for Human-Centred Design. These design characteristics will be thoroughly researched and decided in the context of WP4, WP5 and WP6 of PANTHEON.

4.2.4 UTILIZATION OF DISASTER RESILIENCE SIMULATION MODELS

The utilization of disaster resilience models within the context of the PANTHEON DT involves definition of parameters contributing to disaster resilience, including infrastructure stability, community preparedness, and the ability to recover swiftly after a disaster. Critical infrastructure elements within the smart city should be identified and prioritized, considering guidelines provided by the U.S. National Infrastructure Protection Plan[25]. Vulnerabilities associated with critical infrastructure should be quantified using risk assessment methodologies outlined e.g., in ISO 31000:2018[26] on Risk Management. The focus should extend beyond infrastructure to encompass community resilience, involving community engagement strategies aligned with e.g., ISO 22315:2015 Societal Security[27]. Mathematical and computational models will be deployed to simulate various disaster scenarios, integrating data from the PANTHEON DT and following guidelines such as the ones provided in the National Institute of Standards and Technology (NIST) Community Resilience Planning Guide[28]. Scenario-based simulations will be conducted to assess the smart city's response and recovery mechanisms, aligning with the approach recommended e.g., by the International Electrotechnical

[19] https://www.iso.org/standard/32574.html
[20] https://www.arcgis.com/index.html
[21] https://qgis.org/en/site/
[22] https://thingsboard.io
[23] https://www.etsi.org/committee/cim
[24] https://www.iso.org/standard/77520.html
[25] https://www.cisa.gov/sites/default/files/2022-11/national-infrastructure-protection-plan-2013-508.pdf
[26] https://www.iso.org/standard/65694.html
[27] https://www.iso.org/standard/50052.html
[28] https://www.nist.gov/community-resilience/planning-guide

Commission (IEC) 62351 guidelines[29] standard for the cybersecurity resilience of critical infrastructures. Resilience models could be validated by comparing their outputs with historical data from past disasters, utilizing the guidelines provided e.g., in the Federal Emergency Management Agency (FEMA) HAZUS framework[30] for validation processes. An iterative improvement process should be implemented based on insights gained from simulations and validations, incorporating feedback and lessons learned. Interdisciplinary collaboration among various disciplines, including urban planning, engineering, and social sciences, should be fostered, following e.g., the International Federation of Red Cross and Red Crescent Societies (IFRC) guidelines on community-based disaster risk reduction[31]. Comprehensive documentation of the entire resilience modelling process should be maintained, adhering to e.g., the guidelines set forth in ISO 22313:2020 for Societal Security - Emergency Management - Business Continuity Management Systems[32]. More details and informed decisions on the design and development process for disaster resilience models will be explored later in the PANTHEON project, in the context of WP4.

4.2.5 COMMUNITY ENGAGEMENT AND CO-CREATION

In the design methodology of the PANTHEON DT, community engagement and co-creation play pivotal roles. These steps are crucial for tailoring the PANTHEON DT to the unique needs and aspirations of the community. The community is acknowledged as a key stakeholder, essential for building trust, enhancing social cohesion, and fostering the adoption of the digital twin for disaster management. Stakeholders, including residents, businesses, local authorities, first responders and domain experts, are identified and mapped. A thorough analysis of their interests, concerns, and expectations forms the foundation for tailored engagement strategies. Participatory workshops and focus groups, guided by ISO 37101:2016[33], facilitate open dialogue, idea exchange, and collective problem-solving, incorporating diverse perspectives to address multifaceted challenges. Co-creation sessions go beyond mere feedback collection, involving collaborative design where community members actively contribute to shaping the digital twin's features. This empowers residents to be co-creators, fostering a sense of ownership and commitment to the success of the PANTHEON DT in disaster resilience. Transparent communication channels should be established to inform residents about project objectives, progress, and potential impacts. Transparency, guided by ISO 26000[34] on social responsibility, builds trust and addresses concerns, ensuring community understanding and support. Accessibility initiatives ensure that engagement is inclusive of all community members, considering diverse demographics, languages, and accessibility needs. Inclusivity, guided by ISO 37106:2021[35], is crucial to representing the voices of marginalized or vulnerable groups disproportionately affected by disasters. Continuous feedback mechanisms, such as surveys and online platforms, are implemented to maintain an ongoing dialogue with the community. These mechanisms, aligned with ISO 9001:2015 principles of continuous improvement, ensure that the PANTHEON DT adapts to evolving community needs. Throughout the community engagement process, adherence to legal and ethical considerations, including data privacy, consent, and ethical standards, is paramount. The goal of community engagement and co-creation is to empower residents in the long term. Beyond the initial design phase, mechanisms for ongoing community

[29] https://syc-se.iec.ch/deliveries/cybersecurity-guidelines/security-standards-and-best-practices/iec-62351/
[30] https://www.fema.gov/flood-maps/products-tools/hazus
[31] https://www.ifrc.org/docs/appeals/annual11/MAA0002111p.pdf
[32] https://www.iso.org/standard/75107.html
[33] https://www.iso.org/standard/61885.html
[34] https://www.iso.org/iso-26000-social-responsibility.html
[35] https://www.iso.org/standard/62065.html

involvement in governance and decision-making related to the PANTHEON DT should be established, ensuring sustainability and resilience in the face of evolving disaster scenarios. These concepts have been considered and are extensively researched in PANTHEON, specifically in T2.3, T2.5, T2.6, T3.2 and T1.2.

4.2.6 UTILISATION OF EXISTING SMART CITY DIGITAL TWIN ONTOLOGY

The initiation of a community-centric SCDT such as the one in PANTHEON, could find its foundational structure in Microsoft's Smart Cities Ontology for Digital Twins. This ontology, rooted in the Digital Twins Definition Language (DTDL) and governed by the ETSI CIM NGSI-LD context information management specifications, forms the basis for a comprehensive digital representation of urban environments[36]. The incorporation of key ontology elements in the design process is paramount. The physical location of the community and its intricate infrastructure, encompassing buildings, roads, and utilities, is encapsulated by the Location element. The infrastructure element delineates the physical components comprising buildings, roads, bridges, and utilities. Potential hazards, ranging from natural disasters and industrial accidents to terrorist attacks, are systematically represented by the Hazards element. Risk, a critical facet, quantifies the level of risk associated with each hazard, considering factors like likelihood of occurrence and potential impact. The Response element intricately outlines strategic plans formulated for each identified hazard, covering evacuation routes, emergency shelters, and communication protocols. Resources encompass the available assets allocated to the community for effective disaster management, including emergency personnel, equipment, and supplies. Communication infrastructure for disaster management, spanning emergency alert systems, public address systems, and social media channels, is encapsulated by the Communication element. The Simulation element, vital in refining disaster management plans, involves the creation and utilization of simulation models. These ontology elements serve as a foundational framework, with further refinement and customization tailored to the specific needs of the community and the disaster management plan. Additionally, for comprehensive references in SCDT development, consideration of relevant ontologies such as SmartM2M[37] and SAREF[38], both developed by ETSI, is imperative[39].

4.3 SCDT OPERATION AND MAINTENANCE

Model-Based Systems Engineering (MBSE) is a formalized methodology that is used to support the requirements, design, analysis, verification, and validation associated with the development of complex systems. In contrast to document-centric engineering, MBSE puts models at the center of system design[40].

Following the thorough design and validation of a MBSE process, it becomes essential to manage the ongoing operation and maintenance of the system. Additionally, the MBSE models should be regularly updated to accurately represent any modifications made during the system's operational phase. This includes ensuring the system functions correctly and addressing any encountered issues in a swift and efficient manner. Frequently, this involves establishing a configuration management system to meticulously monitor changes within the models and maintain a historical record of these alterations, aiding in the traceability of system evolution.

[36] https://techcommunity.microsoft.com/t5/internet-of-things-blog/smart-cities-ontology-for-digital-twins/ba-p/2166585
[37] https://www.etsi.org/deliver/etsi_ts/103200_103299/103264/03.01.01_60/ts_103264v030101p.pdf
[38] https://saref.etsi.org
[39] https://digitaltwinhub.co.uk/website_archive/a-survey-of-idms-and-rdls-telecommunication_ontologies_for_dts/
[40] https://insights.sei.cmu.edu/blog/introduction-model-based-systems-engineering-mbse/#:~:text=Model%2Dbased%20systems%20engineering%20(MBSE)%20is%20a%20formalized%20methodology,the%20center%20of%20system%20design.

DTs extend the concept of MBSE, which involves the formalized use of modelling to support various system activities, such as requirements, design, analysis, verification, and validation. MBSE is typically conducted in the conceptual design phase and extends throughout development and later lifecycle phases. Figure below provides an overview of the principal approach in Digital Twin technology. It involves the utilization of data generated by authoring tools and various sources, including client requirements, and operational data, which are converted into output data and simulation models.[41]

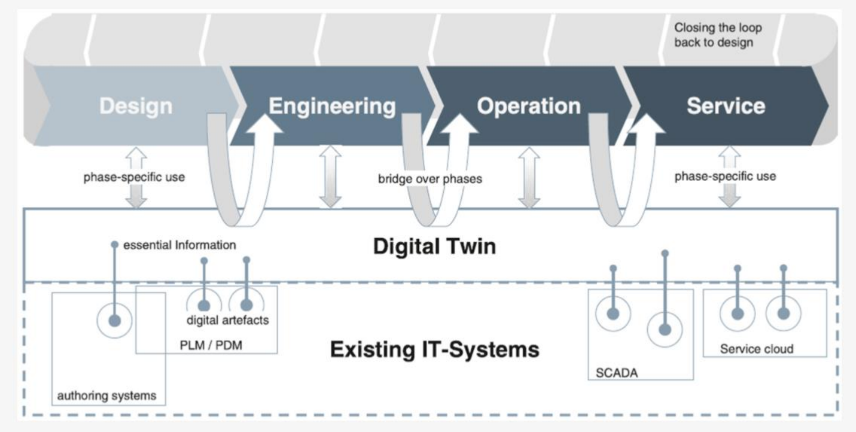

Figure 12 – DT utilises information from different sources and makes it available for succeeding phases of asset lifecycle.42

4.3.1 OPERATING THE SMART CITY DIGITAL TWIN

While its primary application is inherently focused on specific inquiries, DT technology operates in tandem with its physical counterpart. In essence, a major advantage of developing a DT model lies in its capacity to accommodate alterations in the asset's configuration or any physical damage that might affect its performance. This adaptability allows for a comprehensive analysis of the asset's real-world condition.

A DT's capability to support operations during updates is of paramount importance because the primary objective of employing DT technology to pinpoint the precise time and location where damage or failure is likely to occur. Subsequently, this information aids in determining optimal response actions. Operation of a Digital Twin can be broken down into four core concepts that form the baseline of secure and trustworthy operations, namely: System Initialization, Disaster Assessment, Interface Usage, and Security and Privacy.

System Initialization

System initialization is a critical phase in the operation of the SCDT. Data ingestion, the first step in properly operating any Digital Twin during its vanilla execution, is paramount to the system's functionality. PANTHEON's satellite data, in-situ measurements, drone data, and data from critical infrastructures will be ingested efficiently and systematically prior to operation. This process will utilize robust pipelines that collect, validate, and transform data to ensure consistency and integrity upon each initialization of PANTHEON.

[41] Mahmoodian, Mojtaba, Farham Shahrivar, Sujeeva Setunge, and Sam Mazaheri. "Development of digital twin for intelligent maintenance of civil infrastructure." Sustainability 14, no. 14 (2022): 8664.
[42] Boschert, S.; Rosen, R. Digital Twin—The Simulation Aspect; Springer International Publishing: Cham, Switzerland, 2016; pp. 59–74.

Regular updates to these data sources are essential to maintain operating accuracy and relevance. Therefore, a scheduled data retrieval and synchronization mechanisms should be in place, minimizing latency and ensuring the most recent information is available for analysis.

Once data is ingested, constructing and updating the graph model of the urban area is the next critical aspect. PANTHEON's graph algorithms and techniques need to update and manage its graph database that represents the physical and logical relationships between various elements in the urban area. Algorithms for data integration and graph construction should be optimized for efficiency, allowing for near real-time updates as new data becomes available. Parallel processing and distributed computing frameworks should be considered to ensure scalability, especially in large and complex urban environments.

During operation of the DT and for monitoring real-time data input, the digital twin updates the sensing attributes to track the real-time status of the physical twin by collecting disaster observation data through the IoT interface. Since the collected data are in different formats depending on the type of disaster or the IoT device, preprocessing is required for the digital twin to use it. The DT uses data preprocessing FE to process the data.

SCDT assessment operation

The core function of PANTHEON's SCDT is the simulation of disaster propagation and the assessment of its impact on critical infrastructures. To achieve this, testing and validation of PANTHEON's SCDT operation output through its modelling algorithms is paramount. The validation process involves comparing model predictions with historical disaster events to ensure that the model's output aligns with observed outcomes. Additionally, sensitivity analysis and uncertainty quantification should be carried out to understand the limitations and confidence levels associated with the model's predictions.

Once validated, these propagation modelling algorithms must be operated rigorously. This includes users parameterizing and configuring scenario algorithms to simulate various disaster scenarios and stress-testing the system under different conditions. For assessing impact, well-established procedures, such as comparing PANTHEON's SCDT output with standardized risk matrices and criticality analyses, should be applied. Calculations related to asset damage, human safety, and environmental impact should be conducted with precision. Visualization tools, including geographic information systems (GIS) and 3D modelling, should be integrated to convey results effectively.

Proactive disaster scenario development is an essential component. The system should allow users to configure and execute various disaster scenarios to assess preparedness and response strategies. Users must be able to input different parameters, including the type and magnitude of a disaster, to analyze potential outcomes. These scenarios should incorporate dynamic factors such as weather patterns, population density, and transportation networks. The system should then provide real-time analysis and visualization of these scenarios, allowing users to make informed decisions and develop effective disaster mitigation strategies.

Interface Usage

A user-friendly and intuitive dashboard is crucial for real-time monitoring and operation. PANTHEON's SCDT dashboard should provide a unified view of critical data during operation, including disaster simulations, infrastructure status, impact rankings and alert notifications. Data visualization techniques, such as heatmaps, network graphs, and time-series plots, should be integrated to convey complex information concisely. Customization options for user preferences, such as data layers and visual themes, should be made available.

Interactivity is key to user engagement. Users should have access to interactive tools that facilitate data exploration and customization. PANTHEON tools may include filtering, sorting, and drill-down capabilities, as well as the ability to overlay various data layers for comparative analysis. Additionally, users should be able to create custom templates to suit their specific needs.

Integrated alert systems should be configurable based on predefined thresholds, such as damage levels, environmental conditions, or the propagation of a disaster. Alerts should be relayed through PANTHEON notifications to ensure rapid response in emergency situations.

Promoting collaboration and communication among team members using the DT is also of utmost importance for obtaining proper results. The use of functions within the DT tools to share and discuss output and assessments makes it easier to capture feedback and make informed decisions.

Last but not least, the existence of proper documentation, such as system specifications, design documents, UI functionality and report/output explanation is a mandatory asset to any proper DT. PANTHEON will ensure that efficient documentation will exist and remain synchronized with the models.

Security and Privacy

Access control is a fundamental security measure during operation of PANTHEON. Stringent role-based access control should be enforced during operation of PANTHEON's SCDT to limit data exposure to authorized personnel only. User authentication and authorization mechanisms should be integrated to ensure that users can only access data and functionalities relevant to their roles. Additionally, audit trails should be maintained to track access and actions taken within the system, enabling accountability and traceability for future audits.

4.3.2 MAINTENANCE OF THE SMART CITY DIGITAL TWIN

Digital twin systems follow a comprehensive lifecycle, encompassing their inception, design, and development, as well as ongoing maintenance and enhancement. However, once the initial development phase concludeswe need to ensure the longevity and adaptability of the PANTHEON DT under evolving user requirements and expectations. This section delves into essential practices for the maintenance and progression of digital twin systems post-development, providing a technical perspective.

Digital twin maintenance transcends mere bug fixes and issue resolution; it includes incorporating new functionalities, optimizing performance, adapting to evolving platforms, and adhering to evolving regulations. ISO/IEC 14764 standards identify four principal types that can be used for PANTHEON's DT maintenance: corrective, adaptive, perfective, and preventive. Corrective maintenance, often the most urgent, focuses on rectifying defects and faults. Adaptive maintenance involves adapting the digital twin to accommodate environmental changes, such as hardware, operating systems, or external interfaces. Perfective maintenance centers on refining the functionality, usability, and efficiency of the digital twin. Preventive maintenance, on the other hand, adopts proactive measures to mitigate the risk of future issues, encompassing actions like code refactoring, documentation updates, and security enhancements. All these types of maintenance processes need to be aligned and follow a properly defined and staffed maintenance plan.

Establishing a Maintenance Plan

To ensure the efficiency and effectiveness of digital twin maintenance, PANTHEON will develop and utilize a meticulously structured plan. This plan will outline the scope, objectives, priorities, roles, and responsibilities of the maintenance team in detail. Furthermore, it will detail the methods, tools, standards, and metrics that will be employed for monitoring and evaluating maintenance activities and their outcomes. PANTHEON's plan will remain in close alignment with the overarching vision, strategy, and roadmap of the DT, as outlined in Tasks 3.1 and 3.2.

This section presents the fundamental principles that will guide the SCDT Maintenance and User Support tasks within the PANTHEON project. The Maintenance task is responsible to coordinate the continuous maintenance of the sensor, middleware and integration components developed within the project and included in the distribution, preserving at the same time their stability in terms of interface and behavior, so that higher-level frameworks and applications can rely on them[43].

Requests for change (RfC) will be managed adopting a priority-driven approach, so that the risk to compromise the stability of the software deployed in a use-case environment is minimized. Requests for Change will also be properly monitored across the different trackers adopted by Stakeholder Teams. The criterion for such classification is the priority of the RfC, where the priority is the result of the composition of several factors:

- Severity: a measure of the degradation of the quality of service of the affected component;
- Impact: a measure of the effect of the degradation of the quality of service of the affected component;
- Urgency: a measure of how long it will be until the quality of service of the affected component is not significantly degraded;
- Cost: a measure of the resources needed for the management of the change, including the risks associated to the degradation of the quality in case the change is not fully successful.

The evaluation of the priority of an RfC results in one of four possible logical values. Each level implies a very specific behavior for the management of that RfC. The four priority levels and the corresponding behaviors are:

- Immediate: The RfC needs to be addressed as soon as possible. Multiple Immediate-priority changes can be included in the same release, provided that any change does not delay the release significantly. This constraint minimizes the risk of introducing new defects in the new release of the affected component and allows the adoption of special accelerated procedures for its release.
- High: The RfC will be addressed in a next release of the affected component.
- Medium: The RfC will be addressed in the release of the affected component that will be shipped with the next major release.
- Low: There is no target date for addressing the RfC.

User Support tasks are responsible to coordinate the support, together with Stakeholders, to users of the components developed within the project and included in the distribution. The User Support is organized in

[43] SOFTWARE MAINTENANCE AND SUPPORT PLAN, https://cds.cern.ch/record/1277556/files/EMI-DSA1.1-1277556-Software_Maintenance_Support_Plan-v1.0.pdf

three levels, of which only the third one is within the PANTHEON project and provides the most specialized knowledge needed to investigate a reported incident.

To maintain relevance, the plan will be subjected to periodic review and adjustment to reflect the ever-changing needs and feedback of the system's stakeholders. This review will be based on specific KPIs relevant to the PANTHEON Maintenance Tasks:

- **KPI1 - Number of Problems**: Number and trends of problems (defects) submitted in the Defect Tracker(s) (in total and per category) as absolute value and as density over kSLOC.
- **KPI2 - Number of Urgent Changes**: Number of changes (defects or enhancements) with priority Immediate. Information on the number, type and priority of RfCs is extracted from the RfC reports.
- **KPI3 - Change Application Time:** Average time, from incident submission to release, for applying change (possibly per category and priority).

Following a Maintenance Process

Digital twin maintenance is a perpetual and iterative process that demands methodical planning, execution, and evaluation. The process may bear similarities to the Digital Twin Lifecycle (DTLC), albeit with nuanced adjustments according to the type and complexity of the maintenance tasks at hand. Agile methodologies like Scrum or Kanban are well-suited for managing corrective and adaptive maintenance, given the dynamic and unpredictable nature of these activities. Conversely, for perfective and preventive maintenance tasks, which tend to be more stable and predictable, conventional or hybrid methods such as the V-model or Spiral can be judiciously employed. Irrespective of the methodology chosen, strict adherence to software engineering's best practices is crucial. This entails comprehensive testing, quality assurance procedures, meticulous documentation, version control, and rigorous code review processes.

Implementing a Feedback Loop

One of the pivotal aspects of digital twin maintenance revolves around the systematic collection and dissection of feedback from a multitude of sources, encompassing end-users, customers, testers, developers, and management. Feedback emerges as a fundamental tool for identifying issues, requirements, and expectations pertinent to the digital twin system. It offers invaluable insights into areas requiring enhancement and improvement. A diverse array of techniques and tools is available for the collection of feedback, encompassing surveys, interviews, reviews, ratings, analytics, logs, reports, and dedicated bug tracking systems. Furthermore, the establishment of a feedback loop is imperative to facilitate timely and effective communication, response, and action predicated on the feedback received.

Learning and Continuous Improvement

Digital twin maintenance presents not solely a technical challenge but an avenue for continual learning. Feedback, metrics, and insights culled from maintenance activities serve to gauge the performance, quality, and user satisfaction of the digital twin system. Additionally, these inputs enable the identification of areas warranting improvement and augmentation in both the digital twin system and the maintenance process itself. A commitment to continual learning and knowledge application serves as the cornerstone of post-development digital twin sustainability, driving the adoption of best practices and the integration of the latest trends and technologies.

Key maintenance tasks

Efficiency and scalability are pivotal to the system's operation. To handle increasing data volumes and user loads, several measures should be adopted. Scalability should be ensured by using distributed computing architectures, where computational tasks are distributed across multiple nodes or cloud resources to accommodate growing demands. This involves implementing load balancers that distribute incoming traffic evenly to prevent overburdening specific components.

Data caching mechanisms should be implemented to reduce query response times and alleviate database load. Caching strategies, such as content delivery networks (CDNs) and in-memory caching, can significantly improve response times for frequently requested data. Cache invalidation strategies should also be implemented to ensure that cached data remains current and consistent.

Continuous performance monitoring is crucial to identify and address bottlenecks and performance issues. Monitoring tools, including system resource utilization, response times, and error rates, should be deployed to provide real-time insights into system health. Anomaly detection algorithms should be used to trigger alerts in case of abnormal behavior, allowing for proactive intervention.

Regular capacity planning and resource optimization are necessary to ensure cost-effectiveness. Monitoring data should be analyzed to anticipate future resource requirements. This analysis should guide decisions on infrastructure scaling, resource allocation, and the optimization of database queries. Resource allocation should be dynamic, adapting to fluctuations in user demand and data volume.

Data Quality Assurance

Ensuring the continual reliability of the digital twin system hinges on a rigorous approach to data quality assurance. The system must validate incoming data streams to guarantee accuracy and completeness. This validation process necessitates the implementation of robust validation routines capable of detecting and rectifying any data errors or inconsistencies. Moreover, maintaining a comprehensive version history of datasets is imperative for not only establishing traceability but also providing a clear record of changes and their impacts over time.

Algorithm Maintenance

The accuracy and efficiency of the digital twin system's predictive capabilities are intrinsically linked to the precision of its algorithms. Routine calibration of the disaster propagation models is essential to accommodate the evolving conditions inherent to complex urban environments. It is imperative to remain abreast of the latest advancements in research and technology within the field, as these insights inform the continual enhancement and evolution of the algorithms. To ensure their intended performance, any modifications to these algorithms must undergo rigorous testing and validation processes.

Hardware and Software Infrastructure

The fundamental underpinning of the digital twin system lies within its hardware and software infrastructure. Maintaining the integrity and operational stability of this infrastructure is paramount. This demands the continuous application of software patches and upgrades to all components. Additionally, the deployment of advanced monitoring tools is essential for proactively identifying and addressing performance-related issues. Further optimizing resource allocation in a continuous manner is a vital endeavour, allowing the system to align with the ever-evolving computational demands it encounters.

Documentation Practices

In the realm of digital twin systems, the meticulous and comprehensive documentation of various facets is a foundational principle. Detailed records concerning system components and operational procedures should be diligently updated and maintained. Concurrently, the formulation and upkeep of precise change logs provide the requisite transparency to document alterations systematically. Notably, the provisioning of comprehensive training materials serves as a cornerstone in equipping both new users and system administrators with the requisite proficiency to navigate and harness the system's intricacies proficiently.

User Support Framework

The establishment of a robust user support framework is of paramount importance to maintain operational efficiency. This framework will include the establishment of a dedicated help desk, acting as a central point for users to report issues and request timely assistance. Concomitantly, user feedback mechanisms are essential, enabling iterative enhancements that optimize system usability and functionality. Moreover, the institution of thorough training programs for users and administrators ensures that individuals possess the requisite skills and knowledge to competently operate the digital twin system. All aforementioned needs will be tailored to PANTHEON’s use-case execution and relate to its needs and system integration.

5. MONITORING TECHNIQUES, SENSORS AND DATA

5.1 IN-SITU IOT-BASED MONITORING AND DATA

In recent years, unattended and low-cost weather stations utilising cellular and Narrowband IoT[44] (NBIoT) communication technologies have emerged as groundbreaking solutions for monitoring atmospheric conditions. These stations provide highly accurate measurements at fixed intervals, all while maintaining affordability. The following discussion will elaborate on the micro-climate stations used for the implementation of In-Situ IoT-Based monitoring, with a focus on their data collection, transmission, and processing components.

5.1.1 WEATHER STATIONS

Weather stations serve as pivotal data collection devices, characterised by their low cost and low power consumption. Equipped with various sensors, FINT's micro-climate stations are capable of measuring essential atmospheric parameters, including air temperature, air humidity, solar radiation, wind vector, and precipitation. Additionally, they are designed to gather these measurements and transmit them to a central server at predefined intervals, employing cellular technology. This automation significantly simplifies data collection and management once both the micro-climate station and the data-receiving server are set up. To gather all the measurements from the various sensors these stations utilise either wired connections or NBIoT technology to wirelessly transmit the data, before forwarding them to the server.

5.1.2 DATA TRANSMISSION AND MQTT PROTOCOL

To facilitate the data transfer process, micro-climate stations incorporate a component responsible for aggregating measurements and transmitting them via the MQTT messaging protocol. MQTT is an efficient and lightweight Publish/Subscribe protocol, ideal for cases where network bandwidth is limited, and message weight needs to be minimised. Unlike the HTTP protocol, MQTT does not require response messages or delivery assurance, and its payload is lightweight as it lacks the additional headers and information typical of HTTP payloads.

The data gathered by weather stations is sent to an MQTT broker, with each station reserving a specific channel for its data transmission. Subscribed clients can receive data messages from these channels.

5.1.3 WEATHER STATION'S FEATURES

The micro-climate stations provided by the mentioned organisation offer a complete solution for real-time data monitoring. They adhere to data collection practices recommended by the World Meteorological Organization (WMO) and provide a user-friendly interface for viewing current and historical data. These stations are designed to be entirely autonomous, making them suitable for installation in remote locations with limited access to electricity. Their solar and battery-powered setup ensures a life expectancy of over 5 years under normal operating conditions.

[44] https://www.gsma.com/iot/narrow-band-internet-of-things-nb-iot/

5.1.4 SERVER SIDE COMPONENTS

On the server side, the responsibility is to collect measurements sent from micro-climate stations and process the data before persisting it into a structured database. This is achieved by subscribing to MQTT channels where station data is published. The server is implemented in Python and can handle heavy data loads simultaneously without issues. It utilizes the FIWARE ecosystem, designed for efficient IoT data handling, which comprises several essential components:

- **Orion Context Broker:** Orion manages the entire lifecycle of context information, including sensor readings, encompassing updates, queries, registrations, and subscriptions.
- **Quantumleap REST Service:** Quantumleap is responsible for storing and querying historical data in CrateDB, a time-series database.
- **CrateDB:** This time-series database is used to store the historical data collected by micro-climate stations.
- **MongoDB:** This NoSQL database is used to store the latest version of each entity.
- **Mosquitto (MQTT) Broker:** The Mosquitto broker ensures that data is published to the appropriate MQTT channels for further processing.
- **IoT Agent:** The IoT agent subscribes to MQTT channels and is responsible for retrieving data, transforming it into NGSIv2 format, and forwarding it to the Orion Context Broker.

5.1.5 DATA FORMAT AND CONVERSION

Data is transmitted from the weather stations in JSON format. The IoT Agent receives this data and converts it into NGSIv2 format, which is FIWARE's specification for context data representation. NGSIv2 allows data to be defined using unique IDs, and additional metadata can be added for each attribute an entity possesses. This metadata may include information such as entity location, measurement accuracy, unit of measurement, and more. NGSIv2 facilitates the creation of highly detailed and well-structured data, supporting informative graphical representation and data analysis.

In summary, the integration of low-cost weather stations with the mentioned server-side components and the FIWARE ecosystem ensures efficient, accurate, and cost-effective monitoring of atmospheric conditions, while maintaining data integrity and accessibility for informed decision-making and analysis.

5.2 SATELLITE-BASED MONITORING AND DATA

5.2.1 OVERALL

Satellites play a vital role in monitoring and responding to city natural disasters[45]. They provide a valuable source of information that can be used to save lives and reduce damage[46].

There are many satellite-based techniques for monitoring city natural disasters[47]. Some of the most dominant techniques include[48]:

- Optical remote sensing: This technique uses sensors that measure the reflected light from Earth's surface. Optical sensors can be used to detect changes in land cover, such as deforestation or urbanization, which can make an area more vulnerable to natural disasters. They can also be used to identify areas that have been affected by a disaster, such as floods or landslides.
- Radar remote sensing: This technique uses sensors that emit radio waves and measure the reflected waves. Radar sensors can penetrate clouds and darkness, making them useful for monitoring natural disasters at night or in areas with heavy cloud cover. They can also be used to measure the speed and direction of water flow, which can be helpful for predicting floods.
- InSAR (Interferometric Synthetic Aperture Radar): This technique uses two or more radar images of the same area to measure changes in the ground surface. InSAR can be used to detect subtle changes in the ground surface, such as those caused by earthquakes or landslides.
- LiDAR (Light Detection and Ranging): This technique uses a laser to measure the distance to the ground surface. LiDAR can be used to create detailed 3D models of an area, which can be helpful for understanding the impact of a natural disaster.
- Multispectral remote sensing: This technique uses sensors that measure reflected light in multiple wavelengths. Multispectral sensors can be used to identify different types of land cover, such as vegetation, water, and urban areas. This information can be used to assess the risk of natural disasters in different areas.

In addition to these techniques, satellites can also be used to provide communication and navigation services during a disaster. This can be essential for coordinating relief efforts and ensuring the safety of people and property.

5.2.2 THE COPERNICUS SERVICES[49]

The European **Copernicus** services offer support to city natural disasters management. The Copernicus Emergency Management Service (EMS) provides timely and accurate geospatial information derived from

[45] https://www.researchgate.net/publication/308808125_Disaster_monitoring_in_urban_and_remote_areas_using_satellite_stereo_images_A_depth_estimation_approach
[46] https://www.cloudeo.group/blog/cloudeo-blog-space-1/real-time-disaster-monitoring-and-response-with-satellite-data-79#:~:text=Satellite%20data%20can%20also%20be,critical%20infrastructure%20and%20preventing%20damage.
[47] https://ts2.space/en/the-use-of-satellites-in-detecting-natural-disasters/#:~:text=Satellites%20can%20monitor%20changes%20in,or%20the%20spread%20of%20wildfires.
[48] https://dragonflyaerospace.com/earth-observation-and-natural-resource-management/
[49] https://www.copernicus.eu/en/copernicus-services

satellite remote sensing to support all actors involved in the management of natural disasters, man-made emergency situations, and humanitarian crises. The EMS consists of two components:

1. Mapping: This component provides maps and analyses of the affected area before, during, and after a disaster. This information can be used to assess the impact of the disaster, identify areas that need assistance, and plan for recovery.
2. Early warning: This component provides information on the risk of floods, forest fires, and other natural disasters. This information can be used to warn people and take preventive measures.

The Copernicus EMS has been used to support disaster management for several cities, including:

- Floods in Germany in 2021: The EMS was used to map the extent of the flooding and identify areas that needed assistance. This information was used to coordinate relief efforts and help people affected by the floods.
- Forest fires in Greece in 2021 and 2023: The EMS was used to monitor the spread of the fires and identify areas that were at risk. This information was used to evacuate people and protect property.
- Earthquake in Turkey in 2020: The EMS was used to map the damage caused by the earthquake and identify areas that needed assistance. This information was used to coordinate relief efforts and help people affected by the earthquake.

In addition to the Copernicus EMS, there are several other European Copernicus services that can be used to support city natural disasters management. These services include:

- Copernicus Climate Change Service: This service provides information on climate change, such as sea level rise and changes in precipitation patterns. This information can be used to assess the risk of natural disasters and plan for adaptation measures.
- Copernicus Land Monitoring Service: This service provides information on land cover, such as deforestation and urbanization. This information can be used to assess the risk of natural disasters and plan for mitigation measures.
- Copernicus Atmosphere Monitoring Service: This service provides information on the atmosphere, such as air quality and weather forecasts. This information can be used to monitor the conditions that can lead to natural disasters and plan for early warning systems.

These are just a few of the many European Copernicus services that can be used to support city natural disasters management. These services provide valuable information that can be used to save lives and reduce damage.

The dominant US/EU satellite-based techniques and constellations for monitoring city natural disasters are:

1. Landsat: Landsat is a series of Earth observation satellites that have been collecting data since 1972. Landsat satellites carry a variety of sensors that can be used to monitor changes in land cover, such as deforestation or urbanization. They can also be used to identify areas that have been affected by a disaster, such as floods or landslides.
2. Sentinel-2: Sentinel-2 is a series of Earth observation satellites that have been collecting data since 2015. Sentinel-2 satellites carry a variety of sensors that can be used to monitor changes in land cover, vegetation, and water quality. They can also be used to identify areas that have been affected by a disaster, such as floods or wildfires.

3. MODIS (Moderate Resolution Imaging Spectroradiometer): MODIS is an instrument that flies on a number of different satellites, including the Terra and Aqua satellites. MODIS can be used to monitor a variety of Earth surface features, including vegetation, water, and fires. It can also be used to track the movement of clouds and smoke, which can be helpful for predicting the spread of wildfires.
4. GOES (Geostationary Operational Environmental Satellites): GOES satellites are geostationary satellites, which means that they stay in the same position relative to Earth. This makes them well-suited for monitoring weather patterns and tracking the movement of storms. GOES satellites can also be used to monitor the impact of natural disasters, such as floods and hurricanes.
5. SAR (Synthetic Aperture Radar): SAR is a type of radar that can be used to penetrate clouds and darkness. This makes it useful for monitoring natural disasters at night or in areas with heavy cloud cover. SAR can also be used to measure the speed and direction of water flow, which can be helpful for predicting floods.

5.3 AERIAL MONITORING AND DATA

As part of large-scale crisis management, aerial devices, whether based on manned aircraft or drones, are used to acquire geo-referenced data using a variety of sensors. The main types of data are generally obtained using RGB sensors to produce visual images, sensors operating in the near infrared to discern vegetation features, or LIDAR sensors capable of reconstructing overflown surfaces in the form of a 3D point cloud.

Far infrared -also known as thermographic- can also be considered, but its use will be geared more towards the detection of hot spots for fire mapping, night reconnaissance, detecting people in distress or locating moving vehicle engines. This technology is essentially useful in the emergency response phases of a crisis, which are not the focus of the developments and studies carried out as part of the PANTHEON project.

On the other side, hyperspectral sensors could be used for mapping of type of vegetation and building areas, but this technology is still hampered by limitations in terms of resolution and the ability to process low-light images.

There are many other types of sensors that can be used to enhance understanding of analysis situations, such as electromagnetic signal acquisition and analysis systems, but all these devices would be deployed as part of the emergency response phase of crisis management, which is outside the scope of the PANTHEON project.

As far as the collection of visual, infrared or LIDAR data is concerned, and in the context of preparing the crisis management planning environment, the characterization of the data, and the level of information that can be extracted from it, can be broken down according to the following objectives:

- **Fine cartography, possibly topographic:** This is the classic RGB acquisition process, involving photography, geo-referencing and ortho-normalization to ensure that each pixel corresponds to a known and accurate coordinate, within a tolerance of centimeters. The resolution required is generally of the order of ten centimeters (sometimes even more accurate), and the electromagnetic spectrum is the visible one, which may be corrected and calibrated to ensure an acceptable white balance and eliminate the effects of the color temperature of the light illuminating the photographed scene (e.g., setting sun, cloudy sky). Topographical elements, such as shapes and details visible on the ground, whether natural (notably relief and hydrography) or artificial (such as buildings, roads, etc.), can also be included, possibly after identification by AI algorithms.

- **DEM, DSM & DTM generation:** important information for building large-scale crisis scenarios is surface definition. We can distinguish the DEM (Digital Elevation Model) representing the bare-Earth surface, removing all natural and built features, the DSM (Digital Surface Model) capturing both the natural and built/artificial features of the environment, and the DTM (Digital Terrain Model) typically augmenting a DEM, by including vector features of the natural terrain, such as rivers and ridges. All these data can be generated through a succession of RGB shots characterized by a high degree of overlap, and the implementation of photogrammetry algorithms to transform 2D data into a 3D point cloud. LIDAR sensors can also be used, with the distinctive feature that they are direct measurements, and the 3D point cloud is generated directly. The density of points obtained can range from 20pts/m^2 to around a hundred, depending on the raw data acquisition conditions. This type of information is particularly interesting when it comes to developing and implementing hydrographic models to predict the effects of flooding on a given region.
- **Generating 3D volumes using photogrammetry:** Once photogrammetry has generated point clouds, tools can be used to link them together to create small surfaces, and hence volumes. The initial images are then used to colorize these volumes and obtain a true-color 3D volumetric model of the scene overflown. This type of process is particularly useful for building digital models of urban areas, as the precision required to reproduce each street and each building produces a model to be obtained that can subsequently be enhanced with external information (electrical network, sewerage or water supply network, telecoms infrastructure, building types, etc.). This is an essential step in building a city's digital twin. It should be noted that LIDAR cannot achieve this type of result with a satisfactory level of detail, as laser capture pointing in the vertical direction does not always enable vertical surfaces to be rendered.
- **Identification of zone types:** Beyond the topographical elements that can be generated following the acquisition and analysis of data from aerial imagery, there may be an interest in dividing overflown surfaces into different zones with specific characteristics. Urban areas can be isolated from agricultural zones, forests or natural areas. These zones must first be identified and characterized, as the type of sensor used can be defined according to these parameters. Search algorithms, possibly aided by solutions based on AI or by manual processes, will then be used to map the required zones. Subsequently, this type of information can be transformed into higher-level information via possibly empirical correlations in order to extract information such as local population density, biomass (e.g., useful for predicting the spread and intensity of fires), water absorption capacity of the surfaces, resilience of an urban district to heatwaves.
- **Identifying the state of vegetation:** Similarly, there may be an interest in going even further by identifying vegetation types, as this information can be useful for predicting the spread of fires or the effect of a given environment on the temporal evolution of a flood. An area covered with tall vegetation will not have the same impact as a meadow, moor or peat bog. This will also enable the operator to check the condition of firebreaks, and possibly plan maintenance operations in certain local areas. Overflights using hyperspectral cameras can be useful, as the identification of certain wavelengths in the spectrum can be used to characterize vegetation types, and even its state of

health (for example, vegetation showing a hydric stress, and therefore particularly susceptible to fire).

- **State of certain man-made or natural elements:** In the same purpose, man-made structures can be analyzed and catalogued, and their impact on certain types of crises or on the way in which their impact is managed can be characterized. The type and condition of roads can be useful information for setting up an evacuation plan, and the height of buildings can be a useful information to record. Human constructions such as bridges, roads, etc. can be mapped, and the state of natural structures, such as the level of congestion of watercourses, their course, and their capacity to let flows through during periods of heavy rainfall, can be useful information for building hydrographic models.

As seen above, a great deal of information can be gathered and analyzed using aerial means. As mentioned in PANTHEON D2.4 [14], piloted aircrafts will be considered for large-area data collection (e.g., topographic mapping, or 3D photogrammetric modelling of an entire city), while UAVs will be considered for high quality data acquisition (e.g., 3D photogrammetric modelling of a specific infrastructure or building). The specifications of the data to be collected will need to be defined during the next phase of the PANTHEON project.

5.4 OTHER SOURCES OF DATA

The data described in the previous sections will be offered by discrete partners in the consortium. However, other data sources could be utilized to enhance the SCDT's capability to simulate disaster scenarios and practically aid the stakeholders involved in the consortium (JOAFG, HPOL). In the following table (*Table 1*), a brief description is provided of other data sources along with their possible provider that could be utilised in the context of PANTHEON.

Table 1: Additional data and their possible providers

Type of Data	Provider in Greece/Attica	Provider in Austria/Vienna
Geospatial and Environmental	National Observatory of Athens (NOA)[50]: Provides geospatial data related to weather patterns, seismic activities, and environmental conditions.	As a fusion of the Central Institution for Meteorology and Geodynamics (ZAMG)[51]: and the Geologische Bundesanstalt (GBA), GeoSphere Austria[52], (Central Institution for Geology, geophysics, climatology and meteorology) provides geospatial data related to weather patterns, climate, and environmental conditions specific to Vienna.
Building Infrastructure	Technical Chamber of Greece (TEE)[53]: Contains details on construction permits, building	Vienna Building Authority (MA 37)[54]: Contains details on construction permits, building materials, and architectural specifications for a

[50] https://www.noa.gr/en/
[51] https://www.zamg.ac.at/cms/en/
[52] https://www.geosphere.at/de
[53] https://web.tee.gr/en/
[54] https://www.wien.gv.at/wohnen/baupolizei/

	materials, and architectural specifications.	comprehensive understanding of building infrastructure.
Transportation Infrastructure	Hellenic Ministry of Infrastructure and Transport[55]: Offers data on roads, bridges, and public transportation systems for effective disaster management planning[56].	Vienna City Administration - Department of Urban Development and Planning[57]: Offers data on roads, bridges, and public transportation systems, crucial for disaster management planning[58].
	Decentralized Administration of Attica[59]: Offers traffic data on main toll-free highways in Attica[60].	
	Attiki Odos S.A[61]: The operator of the biggest toll motorway (Attiki Odos) in the region of Attica.	
Power Grid Distribution Network Infrastructure	Hellenic Electricity Distribution Network Operator (HEDNO)[62]: HEDNO is responsible for the electricity distribution network in Greece, including the region of Attica. They manage the grid to ensure efficient and secure electricity distribution.	Wiener Netze[63] is the main electricity distribution network operator in Vienna, Austria. They are responsible for the reliable distribution of electricity across the city.
Water Suppy Infrastructure	Hellenic Water Supply and Sewerage Systems Association (EYDAP)[64]: Offers data on water supply systems and infrastructure.	Vienna Water and Sewage Works (Wiener Wasser)[65]: Offers data on water supply systems and infrastructure.
Population and Social	Hellenic Statistical Authority (ELSTAT)[66]: Provides demographic information, population density, and social vulnerability indices.	Statistics Austria[67]: Provides demographic information, population density, and social vulnerability indices specific to Vienna.
Healthcare Infrastructure	Greek Ministry of Health[68]: Contains details on healthcare facilities, medical resources, and the capacity to handle emergencies.	Vienna Hospital Association (KAV)[69]: Contains details on healthcare facilities, medical resources, and the capacity to handle emergencies in Vienna.

[55] https://www.gov.gr/en/upourgeia/upourgeio-upodomon-kai-metaphoron
[56] http://data.nap.gov.gr
[57] https://www.wien.gv.at/english/urbanplanning/
[58] https://www.data.gv.at/en/
[59] https://www.patt.gov.gr/en/
[60] https://www.data.gov.gr/datasets/road_traffic_attica/
[61] https://www.aodos.gr/en/
[62] https://deddie.gr/en/
[63] https://www.wienernetze.at
[64] https://www.eydap.gr/en/Home
[65] https://www.wien.gv.at/english/environment/watersupply/
[66] https://www.statistics.gr/en/home
[67] https://www.statistik.at
[68] https://www.gov.gr/en/upourgeia/upourgeio-ugeias/ugeias
[69] https://gesundheitsverbund.at

Emergency Services	Hellenic Fire Service[70]: Offers information about the location and capabilities of fire stations. Hellenic Police[71]: Provides data on police stations and law enforcement capabilities. Greek National Emergency Center (EKAV)[72]: Contains information on emergency medical services and hospital locations.	Vienna Fire Department (Berufsfeuerwehr Wien)[73]: Offers information about the location and capabilities of fire stations in Vienna. Vienna Police Department (Landespolizeidirektion Wien)[74]: Provides data on police stations and law enforcement capabilities.
Crisis and disaster management	Ministry of Climate Crisis and Civil Protection[75]: This ministry plays a crucial role in managing communication and information systems related to civil protection and crisis response.	Civil Protection and Disaster Management is the National Crisis and Disaster Management (SKKM)[76], which operates under the Federal Ministry of the Interior. The SKKM plays a central role in coordinating national crisis and disaster response efforts, fostering efficient cooperation among various stakeholders to enhance disaster management capabilities in Austria.
Telecommunications Infrastructure	OTE Group (Hellenic Telecommunications Organization)[77]: OTE Group is a leading telecommunications operator in Greece, providing a range of telecommunications services. It plays a crucial role in the telecommunications infrastructure in Attica.	A1 Telekom Austria[78]: A1 is a major telecommunications operator in Austria, providing services such as fixed-line, mobile, and internet communications. It plays a significant role in the telecommunications infrastructure in Vienna.
Natural Gas Transmission System Infrastructure	DESFA (Hellenic Gas Transmission System Operator)[79]: DESFA is responsible for the operation and maintenance of the natural gas transmission system in Greece, including Attica.	Gas Connect Austria[80]: Gas Connect Austria operates the natural gas transmission network in Austria, including Vienna.

70 https://www.fireservice.gr/el
71 https://www.astynomia.gr/hellenic-police/?lang=en
72 https://www.ekab.gr
73 https://berufsfeuerwehr-wien.at
74 https://www.wien.gv.at/verwaltung/organisation/staat/polizei/
75 https://www.gov.gr/en/upourgeia/upourgeio-klimatikes-krises-kai-politikes-prostasias
76 https://www.bmi.gv.at/204_english/start.aspx
77 https://www.cosmote.gr/cs/otegroup/en/omilos_ote.html
78 https://www.a1.net
79 https://www.desfa.gr/en/
80 https://www.gasconnect.at/en/

6. DATA AGGREGATION, ANALYSIS AND PROCESSING

6.1 BIG DATA TYPES, HARVESTING AND AGGREGATION

Smart cities leverage Big Data and the Internet of Things (IoT) to enhance the quality of life for their citizens. Given their intricate nature as the most complex human artifacts, the integration of such technologies becomes a challenging endeavor, necessitating continual data collection, aggregation, and analysis. To effectively address urban challenges and translate them into tangible actions, a systematic approach focused on digital transition must be pursued. Notably, substantial efforts are being invested in constructing city information models that encode details about city objects, their relationships, and support decision-making processes. This endeavor demands a shared knowledge base, reinforced by comprehensive vocabularies and ontologies capable of managing the diverse and overwhelming nature of information.

Undoubtedly, Big Data stands out as a primary facilitator of smart cities. Through the adoption of Big Data and IoT technologies, stakeholders in the city can propel data-driven processes by utilizing shared data rather than relying solely on individual datasets. However, a significant obstacle arises from the scattered distribution of data across various organizations and systems, operating in isolation without standardized semantics and a common technological foundation. The absence of data interoperability poses a challenge, particularly for use case scenarios dependent on linking and analyzing heterogeneous data. Consequently, the establishment of a shared urban data platform for in-depth insights necessitates the development of common data semantics agreed upon by all city stakeholders.

The evaluation of a smart city's performance relies on various key performance indicators (KPIs) and platforms. Additionally, the impact of smart city initiatives is assessed through various procedures. Regrettably, existing approaches and tools for smart city assessment lack continuous monitoring of city processes for data collection and decision guidance. Moreover, smart city interventions often concentrate on singular aspects, such as urban planning, air pollution, mobility, etc.

To enhance city monitoring, proactively identify potential issues, alleviate stagnation, discover new opportunities, and facilitate decision-making through experimentation, the integration of a physical city with a virtual counterpart through digital twinning is essential.

Central to the concept of digital twinning is the City Information Model (CIM), serving as the foundational element for semantically integrating data from diverse and heterogeneous sources. This integration enables a comprehensive and holistic understanding of the city's dynamics and facilitates more informed decision-making for sustainable urban development.

A smart city digital twin is attributed to its utilization of AI and Big Data potential to establish robust models, uncover novel opportunities, and engage with a virtual model to simulate "what-if" scenarios. Big Data plays a crucial role in creating and maintaining these digital twin models.

6.1.1 PROPOSED STRUCTURE OF THE BIG DATA

Figure 13 depicts the proposed big data structure framework of the PANTHEON project.

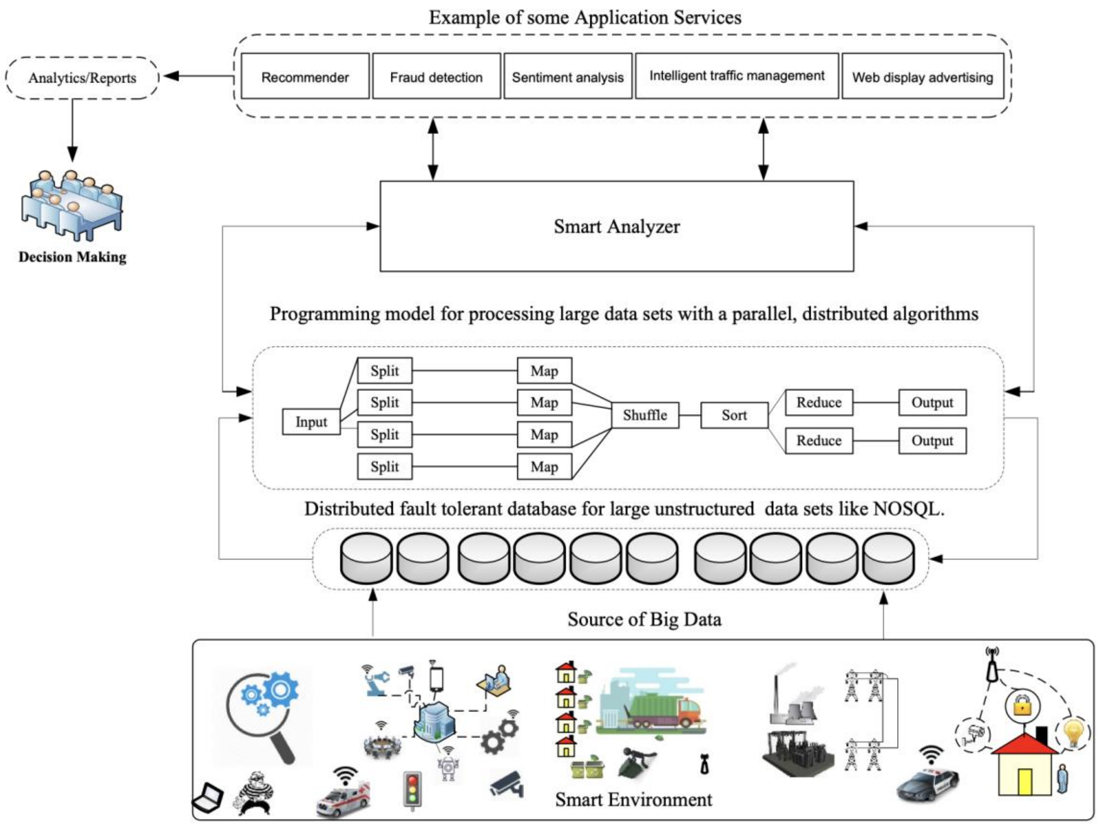

Figure 13 – Construction frame of big data technologies for smart city ([15]).

The first layer is the set of objects and devices connected via local and/or wide-area networks. Most of these objects and devices actively generate a huge amount of unstructured data every second.

In the second layer, all the collected unstructured data are stored in a shared distributed fault-tolerant database located either in the city data center equipped with all network elements or by big data storage such as S3, Google cloud services, and Azure. Within the same layer, the stored data are processed depending on the incoming queries using batch-based programming model. In stream processing, data must be processed quickly so that companies and individuals can react to changes in real time in a smart city environment. Many technologies can help process and act on real-time streaming unstructured data in real time. The smart analysis can be designed using scalable machine learning algorithms or other novel data mining algorithms to provide extraction of patterns and knowledge from large amounts of data, clustering, and classification.

The last layer is the application services, in which people and machines directly interact with each other to make smart decisions. Such applications can be used for different purposes such as recommendation, fraud detection, sentiment analysis, intelligent traffic management, and web display analysis.

6.1.2 BIG DATA TYPES IN PANTHEON

Based on the above proposed structure, the data types used within the PANTHEON project for the SCDT representation can be categorized into distinctive collections as follows:

- **Geospatial Data**: This includes geographic information systems (GIS) data, satellite or UAV imagery, and maps. These types of data are essential for 3D and 2D top-down modelling the physical layouts of the PANTHEON target cities, such as buildings, roads, and infrastructure. The modelling outcomes can then be used for further developing disaster risk management strategies.

- **Sensor Data**: These types include data originating from various sensors placed throughout the city, such as temperature sensors, air quality sensors, traffic cameras, used to monitor and model real-time conditions.
- **In-situ IoT Data**: These types include data originating from on-site Internet of Things (IoT) devices, including smart meters, and infrastructure components that comprise the digital twin models.
- **Utility Data**: These types include information from large infrastructure facilities such as water, electricity, and natural gas providers. They can be used to further monitor potential risks as well as resource management during crisis handling.
- **Transportation Data**: These types include data from traffic cameras, GPS devices, and public transportation systems that are critical for modelling urban mobility. They can be utilized for monitoring traffic patterns in the PANTHEON cities and simulate congestion during disaster events.
- **Social Media Data**: Social media platforms provide a wealth of data on public sentiment, and events that could potentially prove useful in digital twin models for smart cities. This type of data can be used to identify areas where people are congregating and as a result also participate in monitoring traffic patterns in the PANTHEON environment and simulate further congestion patterns during disasters.
- **Weather Data**: Real-time weather data facilitates making predictions for the PANTHEON response stakeholders during extreme weather events.
- **Building Data**: Information about the structures in the city, including architectural plans and building usage, is vital for the PANTHEON project simulating urban environments and building modelling.
- **Energy Data**: Information about energy infrastructure distribution is crucial for optimizing sustainability during extreme conditions or for mitigating further disaster risks.
- **Water Management Data**: In a similar manner, data about water supply infrastructure can be used by the PANTHEON project to provision risk and disaster simulations.
- **Emergency Response Data**: Information on emergency services, response times, and incident reports is vital for optimizing the PANTHEON response teams' stakeholders.
- **Public Health Data**: This type of health data can be utilized by the PANTHEON project simulations to foresee hospital capacities under stress during extreme conditions and disaster events.
- **Security Data**: Data from surveillance systems, access control systems, and security incidents facilitate the PANTHEON project simulations as another aspect for forecasting response teams' management.

These various types of Big Data could be integrated and analyzed by the participating PANTHEON informational systems and data aggregators to create accurate and dynamic digital twin models for the participating smart cities, enabling better decision-making, resource optimization, and future planning.

6.1.3 BIG DATA HARVESTING

Collecting and aggregating big data in general and the above-mentioned collections relevant to the PANTHEON project in particular, involves collecting and consolidating large amounts of data or data streams from the project's multiple and various inhomogeneous sources. Several combined techniques will be required during the project's analysis phases to efficiently harvest, aggregate, and maintain the project's data collections. Such methods can be summarized as follows:

- **Data Integration Tools**: These tools can help in combining data from the project's multiple sources and formats into a single, unified view. Specialized and customized techniques such as data wrangling, fusion, as well as virtualization and visualization will be required for achieving these goals.
- **Data Aggregation Tools**: The PANTHEON project will also require tools specifically designed for aggregating data from its multiple sources. These tools can facilitate data cleansing, transformation, and merging and can operate in customized combination with the data integration tools mentioned above.
- **Data Warehousing**: This step involves the process of collecting and storing the project's data that is shared among different sources into a central storage repository and database system. This process will in turn facilitate efficient data analysis, reporting, and extraction.
- **Data Lakes**: Data lakes are storage repositories that can optionally hold the vast amount of the PANTHEON's raw data collections in their native format until they are possibly needed for reutilization. This technique is potentially provisioned for extreme cases when data must be restructured or re-transformed.
- **Application Programming Interfaces (APIs)**: APIs are a core and central feature of the PANTHEON project. This step enables global data access from all the software applications and solutions that the project will produce, allowing not only the extraction and aggregation of data in a standardized format, but also intercommunication among the project's sub-systems.
- **Data Streaming**: This technique involves the continuous collection and processing of data in real-time from specific PANTHEON data sources that impose this requirement, allowing for the immediate analysis and consumption of data as it is generated.
- **Data Mining and Text Mining**: These techniques that the PANTHEON project might require involve extracting patterns and knowledge from large datasets, including structured and unstructured data, to identify correlations and insights.
- **Machine Learning Algorithms**: This is another technique that might optionally be required and reviewed for the PANTHEON project. Machine learning algorithms can be employed to automatically identify patterns and relationships within large datasets, or to enable the aggregation of data based on specific criteria and parameters according to the proposed digital twin model.
- **Distributed Computing**: Open-source technologies such as Apache Hadoop/Spark as they will be presented in the next sections, enable the processing of large datasets across clusters of computers, allowing for the parallel processing and aggregation of data. This is yet another aspect for consideration under the PANTHEON objectives, according to the efficiency of the proposed implementation.

6.1.4 OPEN-SOURCE BIG DATA HARVESTING AND AGGREGATION SOLUTIONS

Several open-source big data harvesting and aggregation solutions are widely available that provide robust capabilities for collecting, processing, and analyzing large volumes of data. These tools are commonly used in big data projects and can also be applied specifically to the PANTHEON project's requirements. The list below attempts to summarize the most important and influential solutions, however the design and implementation procedures followed by the PANTHEON partners will define which of these or additional tools might be used in the final architecture.

- **Apache Hadoop**: A well-known open-source framework that facilitates the distributed processing of large data sets across clusters of computers using simple programming models. It includes components such as Hadoop Distributed File System (HDFS) and MapReduce.
- **Apache Spark**: An open-source and distributed computing system that provides an interface for programming entire clusters with implicit data parallelism and fault tolerance. Spark supports in-memory processing for high-speed querying and data processing.
- **Apache Storm**: An open-source and distributed real-time computation system used for processing large streams of data in real-time.
- **Apache Flink**: An open-source stream processing framework that provides data distribution, communication, and fault tolerance for distributed computations over data streams.
- **Elasticsearch and Solr**: Distributed, RESTful search and analytics engines that are used for full-text search, structured search, analytics, and all other scenarios that require fast access to large volumes of data.
- **Apache Kafka**: An open-source stream processing platform that is used for building real-time data pipelines and streaming applications. It is capable of handling high volumes of data and enables the building of real-time data-driven applications.
- **RabbitMQ**: An open-source message broker software that facilitates communication between distributed systems by implementing message queues. Key features include support for various messaging protocols, such as AMQP, MQTT, and STOMP, the creation of message queues for asynchronous communication, reliability through acknowledgment and fault tolerance mechanisms, flexible message routing, and the ability to decouple components in a distributed system. RabbitMQ supports the publish-subscribe pattern, clustering for scalability and high availability, and integration with multiple programming languages and platforms. It also offers a management interface for monitoring, security features, and a plugin architecture for extending functionality. Overall, RabbitMQ is usually widely used to improve the efficiency, reliability, and scalability of communication in distributed and decoupled architectures.
- **Apache NiFi**: An open-source data flow tool that enables the automation of data movement between various sources and destinations. It provides a web-based user interface to design, control, and manage the data flow process.
- **Presto**: An open-source distributed SQL query engine for running interactive analytic queries against data sources of all sizes ranging from gigabytes to petabytes. It supports various data sources including Hadoop, Amazon S3, and relational databases.

- **Flume**: An open source, distributed, reliable, and available service for efficiently collecting, aggregating, and moving large amounts of streaming data such as log files, events, and metrics.
- **Druid**: An open-source, column-oriented, distributed data store built for real-time analytics. It is designed for high-performance slice-and-dice analytics over large data sets.
- **PostgreSQL**: As a relational database management system software, it can be used as a data aggregation tool. It is an open-source database program that provides high performance, high availability, and easy scalability.
- **Timescale**: An open-source relational database that is built for handling time-series data. It is designed to provide efficient and scalable storage, processing, and analysis of time-series data, making it a popular choice for managing large-scale time-series workloads. It is widely used in industries such as IoT, finance, monitoring, and analytics, where the efficient management and analysis of time-series data are crucial for making data-driven decisions and deriving valuable insights.
- **InfluxDB**: An open-source time-series database built for handling high write and query loads. It is optimized for capturing, storing, and analyzing time-stamped data, making it a popular choice for applications that require real-time analytics and monitoring. It is widely used in various industries such as IoT, finance, DevOps, and monitoring, where the efficient management and analysis of time-series data are critical for real-time decision-making and performance monitoring.

6.2 DATA ANALYSIS PROCESSING AND REPRESENTATION

6.2.1 DATA ANALYSIS AND PROCESSING METHODS

Data analysis and processing methods encompass a wide range of techniques and approaches to derive meaningful insights and information from data. The below list summarizes these techniques to be considered by the PANTHEON partners and stakeholders during the design and implementation phases.

- **Descriptive Statistics**: This involves summarizing and describing data using measures like mean, median, mode, range, variance, and standard deviation.
- **Data Visualization**: Visualizing data through charts, graphs, and plots to make it easier to understand patterns and trends. Examples include bar charts, scatter plots, and heatmaps. This is a required step for the PANTHEON project in order to support simulations and decision-making tools.
- **Data Cleaning (Data Preprocessing)**: This includes techniques to handle missing data, outliers, and inconsistencies, such as data imputation or error data that can be corrected or specially tagged.
- **Data Transformation**: This involves converting and reshaping data to make it suitable for analysis, as well as making it compatible with the other tools utilized in the project and compliant to PANTHEON's directives.
- **Time Series Analysis and Forecasting**: Analyzing data that is collected or recorded at regular time intervals to identify specific patterns, potentially using methods like autoregressive models and exponential smoothing. Historical data can also be used to predict future values, usually facilitated by forecasting algorithms or machine learning models.

- **Machine Learning and Deep Learning**: Using algorithms and models to perform simulations, make predictions, classify data, and identify patterns. Common machine learning techniques include decision trees, support vector machines, and neural networks. Deep learning is a subset method that utilizes neural networks with multiple layers to analyze and process complex data, such as those consumed by a smart city digital twin model.
- **Regression Analysis**: Modeling the relationship between one or more independent variables and a dependent variable to make predictions. Linear regression and logistic regression are common cases of this method.
- **Simulation and Modeling**: Creating mathematical or computational models to simulate real-world processes and predict outcomes is a crucial aspect of the PANTHEON project.
- **Big Data Processing**: Techniques for handling and analyzing large volumes of data, especially these accompanying a smart city digital twin model. These methods often need to involve distributed computing frameworks such as the open-source Hadoop and Spark. These frameworks are summarized in more detail in the next section for consideration during PANTHEON's implementation phases.

These methods are applied based on the specific nature of the data, the PANTHEON research objective, and the tools available, as they form a crucial role in extracting valuable insights, knowledge, and decision-making factors from the project's available data sets.

6.2.2 OPEN-SOURCE SOLUTIONS FOR DATA ANALYSIS AND PROCESSING

Open-source solutions for data analysis and processing provide flexible and cost-effective options especially for researchers such as the PANTHEON stakeholders to derive insights and make data-driven decisions. The below list summarizes some widely used open-source tools and platforms for data analysis and processing that can be used for the project's objectives:

- **R**: R is a popular open-source programming language and software environment for statistical computing and graphics. It provides a wide variety of statistical and graphical techniques, including linear and nonlinear modeling, time-series analysis, and clustering.
- **Python**: Python is a versatile programming language that offers various libraries for data analysis and processing, such as NumPy, Pandas, and SciPy. It is widely used for tasks such as data manipulation, analysis, and visualization.
- **Apache Hadoop**: Apache Hadoop is an open-source framework for distributed storage and processing of large data sets using a cluster of commodity hardware. It allows for the distributed processing of large datasets across clusters of computers.
- **Apache Spark**: Apache Spark is an open-source unified analytics engine for big data processing. It provides an interface for programming entire clusters with implicit data parallelism and fault tolerance, allowing for in-memory processing for high-speed querying and data processing.
- **Apache Flink**: Apache Flink is an open-source stream processing framework for distributed, high-performing, always-available, and accurate data streaming applications. It is used for real-time data analytics and processing of streaming data.

- **Apache Kafka**: Apache Kafka is an open-source distributed event streaming platform used for building real-time data pipelines and streaming applications. It is capable of handling high volumes of data and enables the building of real-time data-driven applications.
- **Elasticsearch and Solr**: Open-source, distributed search and analytics engines designed for horizontal scalability, reliability, and easy management. They are commonly used for full-text search, structured search, analytics, and more.

These open-source solutions are widely used and supported by a large community of developers and data analysts, making them reliable options for the specific processing tasks that the PANTHEON project will require.

6.2.3 3D DATA PRODUCTION AND VISUALIZATION

Data visualization and storage are characteristics of information-rich 3D city models that can be widely implemented in urban planning, decision-making and urban space management. An ever-growing number of cities are being modeled in 3D. Several cities, Abu Dhabi, for example, have used 3D models and several companies (for example, Google) have also integrated 3D city models in their services. The models are designed in many different ways and used to achieve different objectives, including urban visualization and planning.

Figure 14 – Different design requirements on 3D city model visualization: Photorealistic visualization to give an intuitive impression of existing planned environments (left) and abstract visualization to encode thematic information (right) ([16]).

The creation of a SCDT can be set up with the following steps:

(A) 3D city model

The urban digital twin builds on a solid 3D city model based on geographic data and information such as a digital elevation model (DEM) or a digital building model provided by regional authorities or other public sources as Google maps/Openstreet maps. The digital building model can be supplemented with detailed 3D laser scan data.

In PANTHEON project the decision for the level of detail should be based on the selected cities (Athens/Vienna) and our target of the creation of a SCDT CBDRM (see Figure 14).

(B) Mathematical street network model with space syntax

The application of the theory and method of space syntax, which utilizes a graph theoretical approach, analyze the through movement potentials for cars and pedestrians using the measure of normalized angular choice. This allows us to understand how "central" a street segment is relative to all others in the urban system. This centrality, represented as accessibility, allows us to indicate high to low potentials of usage or, rather, traffic.

(C) Urban mobility simulation

For a better understanding of traffic and people moving behavior, we need a model with a traffic simulation using the open-source software (i.e. SUMO—Simulation of Urban Mobility). The results of the simulation should be displayed in 3D as individual cars, trucks, buses, and bicycles as well as pedestrians moving through the virtual city model.

(D) Sensor and IoT data

As SCDT conceptual model indicates in PATHEON project will collect data from Satellite, Infrastructure, IoT devices, Traffic and aerial devices. Those date somehow should be visualized in the 3D model

(E) People's movement routes, social data, and photographic impression

As PANTHEON is community-based system, data from the people are necessary for finishing the representation of the whole ecosystem. This data will be real time and historical.

6.2.4 SCDT VISUALIZATION SOLUTIONS

There is no widely standardized convention for encoding/creating virtual 3D city models. A first proposal for virtual 3D city models, CityGML, is currently discussed by the Open Geospatial Consortium (OGC). In general, the following data standards are used in practice:

- CityGML, in particular, for building models
- Unity 3D. A popular IDE for creating 3d games and more.
- 3D-Studio MAX object files and VRML files
- ESRI Shapefiles with 2D footprint polygons and height values for each building
- ESRI Shapefiles containing an explicit geometric description of each building in the form of boundary polygons.

6.2.5 DATA REPRESENTATION SOLUTIONS

Open-source solutions for data representation and visualization can form a central role in helping the PANTHEON project's end users understand the complex data sets through informative visualizations and user interface customized screens. Below is a summarized list of some widely used open-source tools and libraries for data representation and visualization:

- **D3.js (Data-Driven Documents)**: A JavaScript library for producing dynamic, interactive data visualizations in web browsers. It allows for the binding of data to a Document Object Model (DOM), enabling the creation of various types of charts and graphs. D3.js is among the most effective visualization tools regarding functionality, features, and design creativity.

- **Plotly**: A JavaScript graphing library that offers a high-level, declarative, and interactive way to generate graphs. It can be used with Python, R, and other programming languages, and it supports various chart types, including bar charts, line charts, and scatter plots.
- **Grafana**: An open-source analytics and monitoring platform that allows for data visualization and monitoring of various metrics. It supports graphing, charting, and alerting for a wide range of data sources.
- **Dygraphs**: An open-source JavaScript library that is used for creating interactive, customizable, and highly versatile charts for representing time-series data. It is well-suited for displaying and exploring dense data sets and time-series data, making it a popular choice for data visualization. It is known for its powerful features and flexibility, making it a preferred tool for creating dynamic and informative visualizations. Overall, it is a powerful and user-friendly data visualization tool that is widely used for creating dynamic and insightful time-series visualizations, enabling users to explore and interpret complex data sets with ease.
- **Leaflet:** An open-source JavaScript library for interactive maps and geographical information systems. It is designed with simplicity, performance, and usability in mind.
- **Graphite**: An open-source monitoring and data visualization tool designed for tracking and graphing the performance of computer systems. It is known for its scalability, real-time processing, and powerful graphing capabilities, making it a popular choice for monitoring and visualizing time-series data. It is widely used in various industries and organizations for monitoring the performance of systems and applications, making it an essential tool for system administrators, developers, and operations teams to track and analyze critical performance metrics.

These open-source solutions can provide a range of options for the stakeholders and implementor partners of the PANTHEON project to create the required data representations and visualizations, also facilitating the decision-making tools. The design and implementation procedures followed by the PANTHEON partners will define which of these or additional tools will be utilized in the final architecture.

7. MACHINE-LEARNING SUPPORTED SIMULATIONS

7.1 SIMULATIONS DESCRIPTION

7.1.1 THE PANTHEON DISASTER PROPAGATION MODEL

PANTHEON's simulations support seventeen critical infrastructure sectors, including information and communications, energy, transportation, water systems and the critical infrastructure sectors identified in multiple official documents[81],[82]. PANTHEON also supports the modeling of different types of dependencies. While logical, informational, and physical dependencies may be defined in service level agreements and are, thus, easier to identify, geographical dependencies may also be included. PANTHEON can automatically identify geographical dependencies based on the locations provided for the critical infrastructure nodes.

A scenario under consideration encompasses existing infrastructures as nodes and is patterned after a documented incident (e.g. an extensive wildfire in Attica). The simulation initiates by a primary event (e.g. the failure of an electric power substation, denoted as node A). This initial event acts as a trigger, leading to a cascade of dependencies and intricate interactions among the nodes, spanning multiple orders and sectors.

The simulation and analysis phase are where PANTHEON comes into play. It takes the input data for the dependencies and computes the entire set of dependency risk paths. These paths encapsulate the different sequences of dependencies and their associated risk values. PANTHEON, as a computational tool, translates these complex interdependencies into a graphical representation that aids in visualizing and comprehending the intricacies of the risk paths within the scenario. Following the analysis, PANTHEON enables users to explore multiple scenarios efficiently. One notable scenario entails a thorough examination and comparison of all potential cascading effects. The tool generates a list of dependency paths, sorted by cumulative risk values, which provides a clear overview of high-risk paths and dependencies that warrant closer attention. Users can also delve into risk mitigation strategies. By identifying paths that exceed a predefined risk threshold, they can prioritize risk mitigation efforts. PANTHEON assists in pinpointing critical nodes and dependencies that require immediate attention to effectively reduce the overall dependency risk.

PANTHEON facilitates comprehensive scenario simulations by modeling and evaluating cascading dependencies, enabling users to prioritize risk mitigation, explore various scenarios, and adapt the analysis to their specific needs and expertise. The execution of scenario simulations using the PANTHEON tool involves a structured process. It begins with defining the scenario, which is typically based on a real-world case, allowing users to model and analyze cascading effects within an urban area that covers a complex system of interconnected infrastructures. In PANTHEON, each node may represent a critical infrastructure or an "autonomous" sub-component of a critical infrastructure (e.g., a power substation) depending on the desired level of analysis. Each node in a graph supports the following attributes:

- **Name:** A unique name for the critical infrastructure node.
- **Critical infrastructure operator:** The critical infrastructure operator responsible for the node. If the analysis is performed at the unit level, then one operator may be responsible for several nodes.

[81] The White House, Presidential Policy Directive – Critical Infrastructure Security and Resilience (PPD-21), Washington, DC, 2013
[82] Commission of the European Communities, Green Paper on a European Programme for Critical Infrastructure Protection, COM(2005)576 Final, Brussels, Belgium, 2005

- **Critical infrastructure sector:** The specific critical infrastructure sector to which the node belongs (e.g., information and communications technology).
- **Critical infrastructure sub-sector:** The specific sub-sector to which the node belongs (e.g., telecommunications).
- **Node location:** The latitude and longitude of the location. This captures geographical dependencies between critical infrastructures and helps evaluate potential threats that concurrently affect multiple nodes.

Directed graphs are used to visualize the relationships (dependencies) between critical infrastructures. A dependency can be defined as a "one-directional reliance of an asset, system, network or collection thereof – within or across sectors – on an input, interaction or other requirement from other sources in order to function properly"[83]. In PANTHEON, dependencies are modeled using a graph G =(N,E), where N is a set of nodes (infrastructures or components) and E is a set of edges (or dependencies). The graph is directional in nature to model dependencies from one critical infrastructure to other critical infrastructures. An edge from node CI_i to node CI_j, i.e., CI_i -> CI_j, denotes a risk relation that is derived from the dependence of infrastructure CI_j on a service provided by infrastructure CI_i[84]. This relation is quantified using the impact and the likelihood of a disruption being realized. The product of these two values is defined as the dependency risk $R_{i;j}$ to infrastructure CI_j due to its dependence on infrastructure CI_i. The numerical value associated with each edge refers to the level of the cascade resulting risk for the receiver due to the dependency. This risk is depicted using a Likert scale [1..9], where 9 is the most severe ranking. Input values $I_{i;j}$ and $L_{i;j}$ are the impact (on a Likert scale) and the likelihood (as a percentage) of a failure experienced in dependency CI_i - CI_j, respectively.

7.1.2 SIMULATION METHOD

Critical to this process is the assignment of input values to each dependency within the scenario. These input values include the likelihood of occurrence and the maximum expected impact for each dependency based on the historical data for the given urban area and potential input from the existing critical infrastructures, such as the types of dependencies to and from each infrastructure and the area that these affects. Additionally, the expected time for the maximum impact to materialize is determined, along with an estimate of the growth rate of the failure. This tabulated information provides the foundation for subsequent simulations and analysis.

The input data for first-order dependencies can be fed to PANTHEON via a spreadsheet, csv, xlsx or via a graphical interface. Given the input data, PANTHEON computes the complete set of dependency risk paths in a time frame for each dependency chain of order no greater than five (see eq. below). Therefore, the algorithmic input for each modeled dependency between infrastructures or their components and processes include at least the following:

- Likelihood of dependency failure for each dependency for a given scenario
- Maximum expected impact estimate for each dependency for a given infrastructure or component
- Expected time taken for the maximum impact to be manifested for each dependency
- Estimate of the growth rate of the failure for each dependency

[83] Department of Homeland Security, NIPP 2013: Partnering for Critical Infrastructure Security and Resilience, Washington, DC, 2013
[84] Stergiopoulos, G., Kotzanikolaou, P., Theocharidou, M., Lykou, G., & Gritzalis, D. (2016). Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures. International Journal of Critical Infrastructure Protection, 12, 46-60.

All the parameters ($L_{i;j}$, $I_{i;j}$, $R_{i;j}$) are defined as input in PANTHEON in order to assess the risk of first-order dependencies. The main input to this method is provided by critical infrastructure owners and operators and refers to the obvious upstream dependencies as mentioned above. Using the first-order dependencies as described in the example above, it is possible to assess the potential nth-order cascading risks using a recursive algorithm. If CI_{Y0} - CI_{Y1} - … - CI_{Yn} is a chain of dependencies, L_{Y0} , … , Y_n is the likelihood of the nth-order cascading effect and I_{Yn-1} , Y_n is the impact of the $CI_{Yn\ 1}$-CI_{Yn} dependency, then the cascading risk exhibited by CI_{Yn} due to the nth-order dependency is computed as[85]:

$$R_{Y_0,\dots,Y_n} = L_{Y_0,\dots,Y_n} \cdot I_{Y_{n-1},Y_n} \equiv \prod_{i=0}^{n-1} L_{Y_i,Y_{i+1}} \cdot I_{Y_{n-1},Y_n}$$

The cumulative dependency risk considers the overall risk exhibited by all the critical infrastructures in the sub-chains of the nth-order dependency. The cumulative dependency risk, denoted as $DR_{Y0;Y1;\dots;Yn}$, is defined as the overall risk produced by an nth-order dependency[86]:

$$DR_{Y_0,\dots,Y_n} = \sum_{i=1}^{n} R_{Y_0,\dots,Y_i}$$

The equation above is implemented inside PANTHEON's assessment algorithm and computes the overall dependency risk as the sum of the dependency risks of the affected nodes in the chain due to a failure realized in the source node of the dependency chain. The risk computation employs a risk matrix that combines the likelihood and incoming impact values of each vertex in the chain.

The dependency risk values computed by PANTHEON's assessment simulation assume a single initiating event (disruption) at a single critical infrastructure that results in cascading disruptions. PANTHEON also covers common-cause failures that simultaneously affect several, seemingly independent critical infrastructures. Such events can cause multiple cascading chains where the impact is introduced to multiple nodes in the graph simultaneously. Thus, the model also captures failures that are simultaneously cascading and common-cause failures. A variety of incidents can serve as initiating events, including accidents, natural disasters, and human-initiated attacks. For example, a common cause initiating event may concurrently affect critical infrastructures (not identified as being directly dependent on each other) due to their physical proximity. Examples include a flood or national strike. In the case of a natural disaster, the value of Likelihood is assessed based on statistics of previous incidents, prognostics, and the presence of vulnerabilities. However, the likelihood of an adversarial attack is more complex; in this case, the likelihood is affected by the motivation and skills of the adversary as well as his perceived impact of the attack. For this reason, expert opinions are commonly elicited, and a worst-case approach is used to obtain the maximum valuation of risk.

[85] Stergiopoulos, George, Panayiotis Kotzanikolaou, Marianthi Theocharidou, Georgia Lykou, and Dimitris Gritzalis. "Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures." International Journal of Critical Infrastructure Protection 12 (2016): 46-60.
[86] Stergiopoulos, George, Panayiotis Kotzanikolaou, Marianthi Theocharidou, Georgia Lykou, and Dimitris Gritzalis. "Time-based critical infrastructure dependency analysis for large-scale and cross-sectoral failures." International Journal of Critical Infrastructure Protection 12 (2016): 46-60.

7.1.3 METHOD VARIATION FOR THE TRANSPORTATION NETWORK

"Likelihood of Congestion" metric for road anticipating road congestion

Each relationship is assigned with a likelihood value, which declares, how likely the junction described by the current relationship is, to be congested. Intuitively, this value is a probability, based on which we can make predictions about each junction's state, at different times. For this to be calculated, we firstly need to check whether each relationship is proportionally fair to the other relationships describing the same junction. Generally, when talking about proportional fairness, we are referring to a system, in which two or more competitive entities are battling for resource control, and how we can maintain balance between them[87]. For example, in a computer network, our goal is to maximise the total throughput while at the same time allowing all the users to experience at least a minimal level of service.

The above is calculated according as follows[88]: *A vector or rates x_r is proportionally fair if it is feasible, that is $x_r \geq 0$, and if for any other feasible vector x^*_r, the aggregate of proportional changes is zero or negative[89]:*

$$\sum_{r \in R} \frac{x_r^* - x_r}{x_r} \leq 0$$

In our case, x_r is the flow of the currently examined relationship, and x^*_r is the vector containing all the flow values for all other relationships referring to the same junction as x_r. We mark each of our relationships as "good" iff they satisfy (3), and "bad" otherwise. Note that he does not have to check for feasibility, since both vectors contain traffic flow values, which are always positive.

After marking all the relationships R as either "good" or "bad", the likelihood value for a relationship *R* is calculated as follows:

$$L_R = \frac{Number\ of\ times\ R\ appears\ marked\ as\ "bad"}{Total\ number\ of\ times\ R\ appears}$$

The "Impact" metric for congested roads

Aside from the likelihood value, each relationship is assigned with an Impact value as well. As the name suggests, this metric declares how severe a possible congestion will be on that edge. Impact thresholds are calculated based on averages of best- and worst-case data entries. The metric is described in levels, ranging from 1 to 5, with 5 being the highest. The impact level for each relationship of a junction is calculated as follows:

1. We create a [1,5] scale from our domain of flows (flow values for a junction).
2. For each relationship, we rescale its flow value into the correct impact level in the range [1,5].

We used the well-known linear scaling algorithm to achieve the above. Its result depicts the number of units of the original interval which are equal to 1 unit of the new interval.

The approach described above is a dynamic one. There is no common scale for all the junctions. This happens, because to calculate the impact level for each junction, we rescale based on its own maximum

[87] Kelly, F. (2003). Fairness and stability of end-to-end congestion control. European journal of control, 9(2-3), 159-176.
[88] Kelly, F. (2003). Fairness and stability of end-to-end congestion control. European journal of control, 9(2-3), 159-176.
[89] Stergiopoulos, G., Valvis, E., Anagnou-Misyris, F., Bozovic, N., & Gritzalis, D. (2017). Interdependency analysis of junctions for congestion mitigation in transportation infrastructures. ACM SIGMETRICS Performance Evaluation Review, 45(2), 119-124.

and minimum flow, so each produced impact level describes how impactful a flow value is for the currently examined junction only. Thus, for each junction, the scale describing its impact levels adapts to its own characteristics (its min and max flow values).

7.1.4 THE PANTHEON DISASTER PROPAGATION MODEL

PANTHEON's modeling and security dependency analysis tool that can be used to evaluate large-scale, cross-sectoral disaster propagation due to infrastructure dependency scenarios. It allows risk assessors, first responders and decision makers to analyze complex dependency graphs during specific disaster scenarios and to identify critical dependency chains before an actual disaster has occurred. PANTHEON's algorithmic method can reveal underestimated dependency risks that need further attention and can be used to efficiently assess alternative risk mitigation strategies, and proactively prepare for mitigation and response during specific types of disasters, thus enhancing urban resilience.

The potential output of PANTHEON is a comprehensive set of potential dependency paths that a selected disaster will take based on input data, intensity, and specificities of the surrounding area, which can be used to project all the cascading effects that may be realized and flag dependency risks that are above a threshold for further attention. PANTHEON's decision support component can be used to run specific scenarios under specific circumstances which may be of interest to risk assessors, including "what-if" scenarios that only consider initiating security events that affect one or some critical infrastructure nodes.

Another aspect of the component's functionality involves comparing sub-paths within disaster risk chains. This allows first responders to identify specific points in the progression of a disaster where mitigation controls are most needed, particularly when specific sub-paths exhibit rapid impact. PANTHEON's algorithmic output offers the capability to analyze common-cause failures. By calculating the sum of dependency risks for all distinct paths originating from a specific node, the tool helps identify nodes that are most critical in common-cause scenarios. It also supports the assignment of weights to these risks based on the likelihood of the initiating event.

To further enhance the analysis, users can customize the tool by adding initiating events and likelihood values, leveraging their expertise and available statistical data. This adaptability empowers users to fine-tune the analysis to consider specific risk scenarios and potential mitigations.

7.1.5 MACHINE-LEARNING CLASSIFICATION RESULTS

In the context of modeling critical urban infrastructures and their interdependencies, the utilization of a machine learning classifier can play a pivotal role in prioritizing and ranking critical dependency chains.

By analyzing historical data and updating PANTHEON's ground truth with real-time information, this classifier can assess the potential risks associated with various interdependencies and provide a ranked list of the most critical ones per scenario identified. The output from the machine learning classifier serves as invaluable information for proactive decision support and mitigation actions. Decision-makers can use this ranked list to allocate resources effectively, plan for contingencies, and implement targeted mitigation strategies. This proactive approach empowers urban authorities to respond swiftly and efficiently to potential disaster scenarios, such as wildfire outbreaks, ensuring the resilience and sustainability of critical urban infrastructures.

7.2 INCORPORATION AND UTILIZATION OF IDENTIFIED DISASTER SCENARIOS

In order to acquire a more comprehensive and complete view in terms of the simulations that will support the decision-making process, the SCDT will also incorporate the most plausible and possible identified disaster scenarios that have been described in the relevant WP2 deliverables (D2.3, D2.4). Specifically, these well-known and described scenarios will be fed into the AI algorithm supporting the simulations and assist in creating realistic simulation scenarios, which will digitally represent the most possible to happen disasters and their impacts. In that sense, the AI algorithm will be also adequately trained based on realistic pre-existing scenarios and will enhance its ability to produce useful outcomes that will support the decision-making process.

In more details, the specific scenarios will be represented in the simulation module, beginning with the creation of a digital representation of the area of interest. Subsequently, the disaster conditions will be digitally implemented and utilized, while the final impacts will be created as the simulation outcomes. The whole procedure, assisted by the AI algorithm and the rest of the simulation inputs (e.g. data, community characteristics, etc.) will provide a holistic digital depiction of the area under disaster and the corresponding impacts.

7.3 COMMUNITY CHARACTERISTICS RELATED INPUTS

The community characteristics in PANTHEON need to be incorporated into the PANTHEON SCDT architecture, so that these characteristics can be considered when the scenarios are simulated. These characteristics can be broadly categorized into demographics-related, health-related, social connection-related, resource-related, exposure and protection-related, and knowledge and awareness-related. Based on these categories, specific Vulnerability Capacity Indicators (VC Indicators) can be used for sufficiently representing community characteristics of interest. These indicators could be incorporated in the simulation scenarios by updating the relevant weights of the connected and directional graphs in simulation, that reflect the vulnerability of specific communities or areas that are mapped into parts of the relevant simulation graph. The VC Indicators that could be utilized by the PANTHEON SCDT have been extensively researched in D2.3, and the relevant table from this deliverable is provided in Table 2 for self-containment purposes. The most relevant VC Indicators for each simulated disaster scenario should be selected and incorporated as specified previously. Finally, relevant data sources (such as statistics databases) could be reached to provide up-to-date information for each VC indicator.

Table 2: Vulnerability indicators devised for the focus regions Vienna and Athens

Vulnerability Indicator	Reasons for vulnerability	Affected groups and covered factors	Dimensions	Potential measurement
Life stage-related				
Advanced age	Lack of capacity to respond to disasters, dependency on others, mobility problems	Elderly people, lack of physical endurance	social physical	% of people over 65 years of age in the population

Young age	Lack of capacity to respond to disasters, dependency on others, mobility problems	Children/minors, students, households with many children, lack of physical endurance	social physical	% of people under 15 years of age in the population
Family status	Care-giving responsibilitie s Financial resources	Single parent families with minor children, households with (many) children	social economic	% of single-parent families with minor children in the population
Health-related				
Mental health	Lack of capacity to respond to disasters, dependency on others, possible problems with medication	People with mental disorder/disability/illness	social	% of people with mental disorder/disability/illne ss in the population
Physical health	Lack of capacity to respond to disasters, dependency on others, mobility problems, possible problems with medication	People with physical disorder/disability/illness, lack of physical endurance	physical	% of people with physical disorder/disability/illne ss in the population
Mobility	Complications during evacuation or concerning self-protection	Elderly people, children/minors, pregnant people, people with physical disorder/disability/illness, lack of physical endurance, overweight people	Social physical	% of people in the population with known mobility problems
Pregnancy	Mobility problems, possible health complications, teratogens	Pregnant people, lack of physical endurance, women	social physical	% of known pregnant people in the population
Social connection-related				
Migration background	Language barriers, possible insufficient social integration	Migrants, refugees, asylum seekers	Cultural social political	% of first-generation immigrant households, refugees and asylum seekers in the population

	and awareness of local disaster management plans, living conditions and financial resources			
Language barriers	Problems with communication between emergency services/ official bodies and locals, vulnerability to misinformation	Migrants, refugees, asylum seekers, people with mental disorder/disability/illness, tourists	Cultural social political	% of people with insufficient skills in the local language in the population
Social isolation	Lack of social network, lack of possible aid in case of problems	The elderly living alone, the socially isolated, homeless people	Social cultural	% of single-person households in the area
Resource-related				
Financial resources	Finances influence the capacity to respond to or recover from disasters, as individual resources are needed to prepare for disasters as well as recover and rebuild after they happen	People with low income	economic social	Median income of inhabitants
Potentially affected agricultural areas	Potential threat to livelihoods and food sources	Workers, animals	Physical environmental economic	% of the region being farmed land situated in the hazard zone
Vegetation/ecosystem	Certain kinds of vegetation recover easily while others are more vulnerable to wildfires, storms, floods	General population, e.g., summer season in Greece, heat waves in Vienna	environmental	Qualitative / Resilience of the ecosystem, particularly vulnerable areas (see hazard-specific vulnerabilities and D2.2 (Triantafyllou & Apostolopoulou, 2023))

	or other hazards			
Potential job losses	Potential threat to livelihoods as well as the economy and infrastructure	General population, esp. people with increased exposure, like workers, companies, industries, institutions	Social economic	Number of potential jobs lost per 1,000 inhabitants in the area
Exposure and protection-related				
Population density	Higher population density means more people are at risk while also creating potential issues during evacuation	General population	Physical, social, cultural	Number of inhabitants per square kilometer
Increased exposure	Increased exposure of e.g., healthcare workers to pathogens or first responders to aftershocks puts them at risk	People with increased exposure, like workers, active people (people doing sports outside), animals, companies/industries/institutions, people living in basements or ground floors	Physical social environmental	% of people working and living in the potential hazard area out of total population (including people living in top-floor apartments for heatwaves, in basements and ground floors for floods, and people living next to forests for wildfires)
Homelessness	Financial resources and social isolation, living conditions and resulting exposure to environmental conditions	Homeless people, people with low income	social physical economic	% of unhoused people in the population
Poor housing quality	Increased risk of collapse or damage, e.g., during earthquakes or floods	People living in houses with poor housing quality/ old or insufficient regulations, people with low income, lack of cooling, lack of urban planning	Physical political economic	% of population living in houses with poor structural integrity and/ or insufficient regulations
Special accommodations	Dependency on others, possible problems with mobility and evacuation, possible problems with	Students, the elderly, children/minors, pregnant people, workers, homeless people, migrants, refugees, asylum seekers, People with physical or mental disorder/disability/illness, lack of cooling, women	Physical social economic	% of people living or staying in special accommodations in the area (hospitals, prisons, care homes, homeless shelters and women's shelters…)

	heating and cooling, dependence on working infrastructure, electricity			
Knowledge and awareness-related				
Lack of disaster awareness or disaster education	Lack of knowledge on the best way to behave in a disaster situation puts people at risk, lack of awareness may also cause hazards, e.g., in the case of man-made wildfires or other man-made hazards	People untrained/uneducated in disasters, digitally illiterate people, people with lack of risk awareness or situational awareness, tourists	Social cultural political	Qualitative / Number of disaster preparedness trainings/education programs available per 1,000 inhabitants
Lack of familiarity with the environment/Local knowledge	Tourists are vulnerable due to unfamiliarity with the terrain, the local safety measures, and the local language	Tourists, newcomers, students, children, elderly	Cultural social	Qualitative / % of people without familiarity with the environment in the area during a typical day

8. ARTIFICIAL-INTELLIGENCE BASED DECISION SUPPORT SYSTEM

8.1 DECISION SUPPORT SYSTEMS FOR COMMUNITY-BASED DISASTER MANAGEMENT

8.1.1 DECISION SUPPORT SYSTEMS

A DSS is an information system that supports decision-making by selecting the best option by developing and comparing multiple alternatives to solve various issues ([17]).

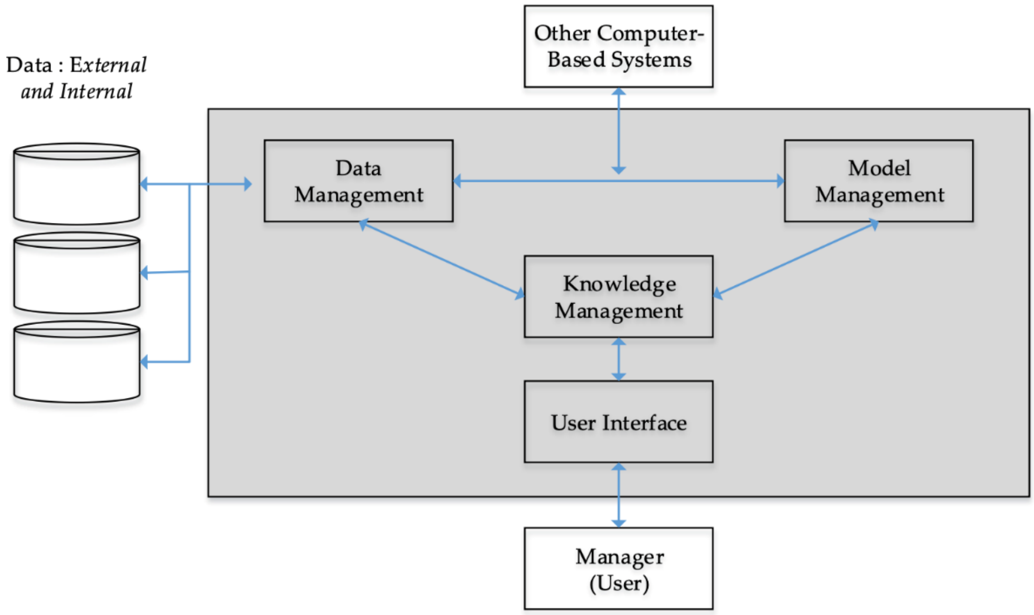

Figure 15 – DSS components.

DSSs have a long history of development. The evolution of the decision support concept can be traced back to theoretical studies on organizational decision-making conducted at the Carnegie Institute of Technology in the late 1950s and early 1960s, coupled with subsequent implementation efforts in the 1960s.The field of DSS emerged as a distinct area of research in the mid-1970s, gaining momentum throughout the 1980s ([18]). During the latter part of the 1980s, there was a notable transition from single-user and model-oriented DSS to the development of executive information systems (EIS), group decision support systems (GDSS), and organizational decision support systems (ODSS). The definition and scope of DSS underwent significant changes over the years. In the 1970s, DSS was characterized as "a computer-based system to aid decision making" ([19]). In the 1980s, the expectation was for DSS to offer systems using suitable and available technology to improve the effectiveness of managerial and professional activities. Towards the end of the 1980s, DSS faced a new challenge related to the design of intelligent workstations. Since then the use of DSSs has grown rapidly, with the aid of data analysis tools.

Figure 15 shows the main components of a DSS:

(a) Data management. This is a Database system that stores all the data needed for the system for the decision making.

(b) Model management. This unit stores various models that are necessary for the decision making and a model-based management system (MBMS). The MBMS provides functions to develop, modify and control the system models that needed for the decisions.

(c) User interface. This module is the interface between the user and the DSS. The user can input, export data and perfume procedures and scenarios.

(d) Knowledge management. This module provides decision-makers with knowledge and alternative solutions for problem solving.

(e) Users: The users who use a DSS are primarily the managers who are responsible for important decisions. They can choose the most appropriate model from the model base, import data directly into the model, and then evaluate and analyze the options to determine the best alternative.

8.1.2 USING DSS IN CBDRM

As part of the PANTHEON project, an AI-based DSS will be used with (but not limited to) Community-Based Disaster Risk Management (CBDRM). This aims to provide tools in decision-making processes related to disaster risk reduction and response.

While utilizing DSSs to aid disaster recovery efforts has proven highly advantageous, these systems do come with certain drawbacks. One notable limitation is the challenge of freely and swiftly exchanging data among individuals and organizations due to differences or incompatibilities in systems and technologies. Despite this, managers widely employ DSSs, and efforts have been made to overcome these drawbacks.

Rajabifard et al. in [20] successfully employed an intelligent disaster DSS (IDDSS) as a platform for integrating road, traffic, geographic, economic, and meteorological data. Particularly, IDDSSs are instrumental in managing road networks during floods, providing law enforcement with precise locations to establish traffic management points (TMPs) during emergencies and preventing hazardous traffic scenarios. In a different context, Ishak et al. ([21]) developed a conceptual model for a smart DSS dedicated to reservoir operations during emergencies such as heavy rainfall. This model assists reservoir operators in making informed decisions on releasing water to ensure ample space and prevent local flooding.

Additionally, Artificial Intelligence (AI) has been seamlessly integrated into DSSs to enhance decision-making efficiency. Notably, Dijkstra's algorithm, known for finding the shortest path between two points, has found applications in diverse areas. For instance, it has been employed in forest fire simulations ([22]) and optimizing route planning efficiency ([23]). In 2011, Akay et al. ([24]) further refined this algorithm by incorporating Geographic Information System (GIS), aiding firefighters in determining the fastest and safest access routes. The system relies on extensive spatial databases, encompassing road systems and land data. Barrier systems have also been implemented to simulate scenarios with restricted roads, serving not only to identify the quickest routes but also to assist firefighters in anticipating unforeseen circumstances and determining safe and reliable routes.
To deal with disasters in PANTHEON project should use an effective disaster management system. However, disaster management systems depend on various data and information and knowledge of previous disasters. Therefore, coordination between the relevant agencies in Athens and Vienna is necessary to integrate the data effectively. A DSS is unable to prevent all catastrophic damage; however, it can mitigate the potential risks by developing early warning strategies and preparing appropriate options.

8.2 PANTHEON AI-BASED DSS

8.2.1 METHODOLOGY

The DSS employed for disaster response management within the framework of a Community-based Smart City Digital Twin (SCDT) represents a paradigm shift in the approach towards addressing vulnerabilities in critical infrastructure protection. This innovative methodology integrates the insights derived from time-based critical infrastructure dependency analysis, as elucidated in [25] and [26], through the application of graph modelling techniques. The synergistic amalgamation of these methodologies establishes a cutting-edge foundation that significantly advances our capabilities in mitigating the complex challenges associated with disaster response management. To comprehend the intricacies of this methodology, it is imperative to delve into the foundational concepts of time-based critical infrastructure dependency analysis and graph modelling. The work in [25], rooted in the temporal aspects of critical infrastructure dependencies, provides a nuanced understanding of the cascading failures that may ensue during large-scale disruptions. The work in [26], further contributed to this knowledge by elucidating the cross-sectoral implications of interdependent infrastructures. The integration of these time-based insights into the broader context of disaster response management heralds a shift towards a more nuanced, temporally aware approach.

The utilization of graph modelling as a pivotal component of this methodology is underpinned by the inherent complexity of urban infrastructures and the interwoven nature of their dependencies. Graph modelling, as exemplified by the works in [25] and [26], encapsulates the intricate relationships between different infrastructure elements, allowing for a holistic representation of dependencies. This modelling approach is not merely a theoretical construct but a pragmatic tool that captures the dynamic interplay between critical infrastructures during large-scale and cross-sectoral disruptions. The heart of the methodology lies in its ability to seamlessly integrate the graph modelling approach into the SCDT of PANTHEON. PANTHEON, as a comprehensive digital replica of the urban environment, becomes the canvas upon which the dynamics of infrastructural interdependencies are portrayed. This integration enables the DSS to dynamically simulate cascading failures over time, accounting for the intricate temporal characteristics of dependencies. The temporal dimension introduced by the time-based critical infrastructure dependency analysis is a key differentiator in the disaster response management landscape. By considering the temporal evolution of dependencies, the DSS can provide decision-makers with a more comprehensive understanding of the potential impacts on critical infrastructures. The system moves beyond static representations and embraces the fluidity of dependencies during hazardous scenarios, thus enhancing the adaptability and resilience of urban infrastructures. The operationalization of this methodology within PANTHEON SCDT goes beyond the established norms of disaster response management. Real-time spatial and environmental data are seamlessly integrated into the modelling framework, injecting a layer of dynamism that was previously absent. The system becomes a living, breathing entity that responds to the pulse of the urban environment in real-time. This real-time data integration enhances the accuracy and relevance of the simulations, aligning the DSS with the ever-changing landscape of urban dynamics.

Furthermore, the incorporation of 3D simulations over the graph models elevates the system's capability for hazard proactive simulation. The visual representation of cascading failures in a three-dimensional space not only aids in comprehension but also provides a tangible tool for decision-makers to assess and strategize. The immersive nature of 3D simulations allows for a more intuitive exploration of potential scenarios, fostering a deeper understanding of the spatial and temporal dimensions of disasters. The participatory approach embedded in the DSS further amplifies its functionalities. By actively involving sensitive groups such as infrastructure operators and vulnerable communities, the system becomes a collaborative platform for risk analysis. Stakeholders contribute unique insights that enrich the modelling process, ensuring that the analyses are not only scientifically rigorous but also socially inclusive. This participatory approach fosters a sense of shared responsibility, empowering stakeholders to actively engage in the enhancement of the city's resilience and preparedness. In addition, the DSS leverages state-of-the-art machine learning algorithms, including Random Forest and Neural Networks, to perform intricate data analysis [27]. Trained on vast repositories of historical data, these algorithms autonomously recognize patterns, anomalies, and potential disaster risks. The passive nature of this analysis involves the algorithms autonomously sifting through immense datasets, enabling the DSS to passively glean insights that might elude conventional data analysis methods. In harnessing the power of historical data, the machine learning models within the DSS could also embark on predictive analytics journeys. For instance, in regions prone to flooding, the system passively predicts potential flooding events by analysing historical rainfall patterns and correlating them with past instances of flooding [27]. This predictive capacity allows decision-makers to proactively plan and implement measures to mitigate the impacts of impending disasters.

8.2.2 OPERATION

Graph Modelling Integration

The core operational facet of the DSS lies in its adept utilization of a graph modelling approach within the SCDT of PANTHEON. This methodological choice is underpinned by the imperative need to comprehend the intricate interdependencies among critical infrastructures during disaster scenarios. A comprehensive exploration of these dependencies involves the dynamic simulation of cascading failures over time, a task seamlessly accomplished by the amalgamation of graph modelling techniques and the SCDT framework. The integration of a graph modelling approach within PANTHEON facilitates a nuanced analysis of various dependencies and their temporal characteristics. This sophistication is critical for enhancing decision-makers' understanding of potential impacts on critical infrastructures. Through the passive observation and meticulous consideration of the evolving nature of dependencies, decision-makers are empowered with a more profound comprehension of the cascading effects that may transpire during large-scale disruptions. This nuanced understanding is instrumental in informing strategic decisions aimed at mitigating the repercussions of cascading failures.

Real-time Data Utilisation

PANTHEON SCDT is intended to distinguish itself by surpassing the limitations of prior research through the judicious utilization of real-time spatial and environmental data. The system's capacity to integrate and harness real-time data constitutes a paradigm shift in disaster response management. This integration is not merely an incremental enhancement; rather, it is a transformative leap toward a more adaptive and responsive system. The utilization of real-time spatial and environmental data serves as the lifeblood of PANTHEON SCDT's operational efficacy. The system actively taps into diverse sources of real-time data, encompassing spatial information and environmental variables. This active data integration endows the system with the capability to adapt and respond dynamically to evolving disaster scenarios. The passive assimilation of real-time data ensures that the system remains acutely attuned to the ever-changing urban landscape, thereby enhancing its predictive and proactive capabilities.

3D Simulations
A pivotal facet of the DSS's operational framework lies in its incorporation of three-dimensional (3D) simulations overlaid upon the graph models within PANTHEON SCDT. This integration transcends the conventional boundaries of disaster response simulations, providing decision-makers with a visual representation that transcends the two-dimensional constraints of traditional models. The passive engagement with 3D simulations offers decision-makers an immersive and intuitive means of comprehending hazard scenarios. The 3D simulations encapsulate hazard scenarios in a visually rich and dynamic environment, enabling decision-makers to passively observe the spatial and temporal dimensions of potential disasters. This passive immersion enhances decision-makers' situational awareness and fosters a more profound understanding of the potential impacts on critical infrastructures. The incorporation of 3D simulations is not merely a cosmetic enhancement but a substantive augmentation of the DSS's operational capabilities, enabling dynamic hazard proactive simulation. In essence, the passive utilization of graph modelling, real-time data, and 3D simulations within the operational framework of the DSS in a Community-based Smart City Digital Twin establishes a symbiotic relationship between advanced scientific methodologies and the imperative need for adaptive and intuitive disaster response systems.

Continuous Learning Mechanism, Predictive Analysis, and Impact Assessment
A distinctive feature of the DSS is its incorporation of a continuous learning mechanism. The machine learning algorithms passively adapt and improve over time, a process fuelled by feedback from real disaster events and the efficacy of implemented response strategies [26]. This passive evolution ensures that the DSS remains at the forefront of disaster response technologies, learning and refining its analytical capabilities with each new event. The DSS's predictive analytics extend to comprehensive scenario-based modelling. It employs predictive analytics not only for individual events but also to model various disaster scenarios such as earthquakes, floods, and other potential crises [26]. Through passive simulation, decision-makers gain insights into the potential impacts of these scenarios, allowing for the formulation of nuanced and effective response strategies. Predicted disaster scenarios are not merely presented in isolation; they undergo a passive impact assessment process. This involves the evaluation of the potential impact on the community, considering factors such as the vulnerability of different areas, critical infrastructure, and population density [26]. The passive nature of this assessment ensures that decision-makers are equipped with a holistic understanding of the potential consequences, enabling the implementation of targeted and effective response measures.

8.2.3 FUNCTIONALITIES

Dynamic Risk Analysis
The pivotal functionality of the DSS lies in its adept facilitation of dynamic risk analysis. This is achieved through the continuous simulation of cascading failures and dependencies within the SCDT of PANTHEON, integrating real-time data inputs. The passive engagement with this sophisticated simulation mechanism ensures that decision-makers are not only presented with a real-time snapshot of the evolving disaster scenario but also equipped with the most up-to-date information necessary for formulating effective response strategies. The utilization of dynamic risk analysis within the DSS transcends conventional risk management paradigms. The system passively observes and simulates the cascading effects that may unfold during large-scale disruptions, considering various dependencies and temporal characteristics. This strategic approach ensures that decision-makers possess a comprehensive and evolving understanding of potential

impacts on critical infrastructures. The passive simulation of cascading failures is not merely a predictive exercise but a dynamic process that unfolds in tandem with the evolving nature of disaster scenarios.

Stakeholder Empowerment

Inclusivity is a cardinal aspect of the DSS's functionalities, realized through the active incorporation of input from sensitive groups, including infrastructure operators and vulnerable communities. This participatory approach fosters a sense of shared responsibility among stakeholders, transcending traditional top-down decision-making structures [28], [29]. The passive involvement of these stakeholders in the risk analysis process goes beyond tokenistic engagement, empowering them to actively contribute to the formulation of risk assessments. The participatory approach within the DSS establishes a symbiotic relationship between the system and its stakeholders. Through passive engagement, infrastructure operators and vulnerable communities contribute unique insights and nuanced perspectives that might otherwise be overlooked. This collaborative approach ensures that the risk analysis process is enriched with diverse viewpoints, enhancing the overall effectiveness of response strategies. The passive inclusion of stakeholders in the decision-making process establishes a foundation for community-centric disaster response management.

Enhanced Accuracy

A synergistic amalgamation of graph modeling, real-time data integration, and stakeholder input is pivotal in enhancing the accuracy of risk assessments within the DSS. This multifaceted approach ensures that risk assessments are not confined to theoretical models but actively incorporate real-world dynamics [28], [29]. The passive assimilation of diverse data sources, including real-time spatial and environmental data, enriches the accuracy of risk assessments by providing decision-makers with a holistic and nuanced understanding of the disaster scenario. The passive inclusion of graph modeling within the DSS goes beyond static representations, dynamically simulating the evolving nature of interdependencies. This ensures that risk assessments are not constrained by static models but adapt to the dynamic and complex nature of urban landscapes. The passive amalgamation of real-time data sources ensures that the DSS remains attuned to the ever-changing urban environment, contributing to the adaptability and responsiveness of risk assessments.

9. SCDT PLATFORM USER INTERFACE

9.1 USER INTERFACE ARCHITECTURE

SCDTs are gaining increasing significance in academic, government, and industrial sectors. These digital representations offer a virtual context that faithfully mirrors a real city, typically utilizing 3D models of buildings enriched with comprehensive information from various sources, including IoT sensors, heatmaps, analytic services, and building information modeling. SCDTs serve as essential tools for city decision-makers and stakeholders, enabling real-time observation of the city's status and facilitating analysis and simulations across diverse domains such as urban planning, mobility, energy, disaster analysis and prevention, air pollution monitoring, and city planning.

Addressing the challenge of 3D city modeling for realistic virtual visualizations, recent works have focused on city-wide areas. The production, handling, and processing of these 3D models remain formidable tasks. CityGML has proposed a format to display data on a web interface, defining different Levels of Detail (LoD) for the model. LoD0 includes 2D maps and 3D terrain, LoD1 introduces basic 3D building models, LoD2 enhances them with 3D roof structures, LoD3 incorporates realistic textures, and LoD4 describes building interiors. CityGML3.0 further integrates Building Information Modeling (BIM) using the Industrial Foundation Class (IFC) format.

A comprehensive SCDT should encompass information about Point of Interest (POI) locations, positions and readings of IoT sensors, heatmaps illustrating, for instance, the dispersion of pollutants, as well as paths (e.g., cycling paths) and areas (e.g., city districts). To augment the 3D model with such diverse knowledge, the SCDT needs to be embedded in a platform capable of modeling various data types. This platform should adeptly handle static and real-time data, allowing for manipulation, indexing, and retrieval through specific APIs.

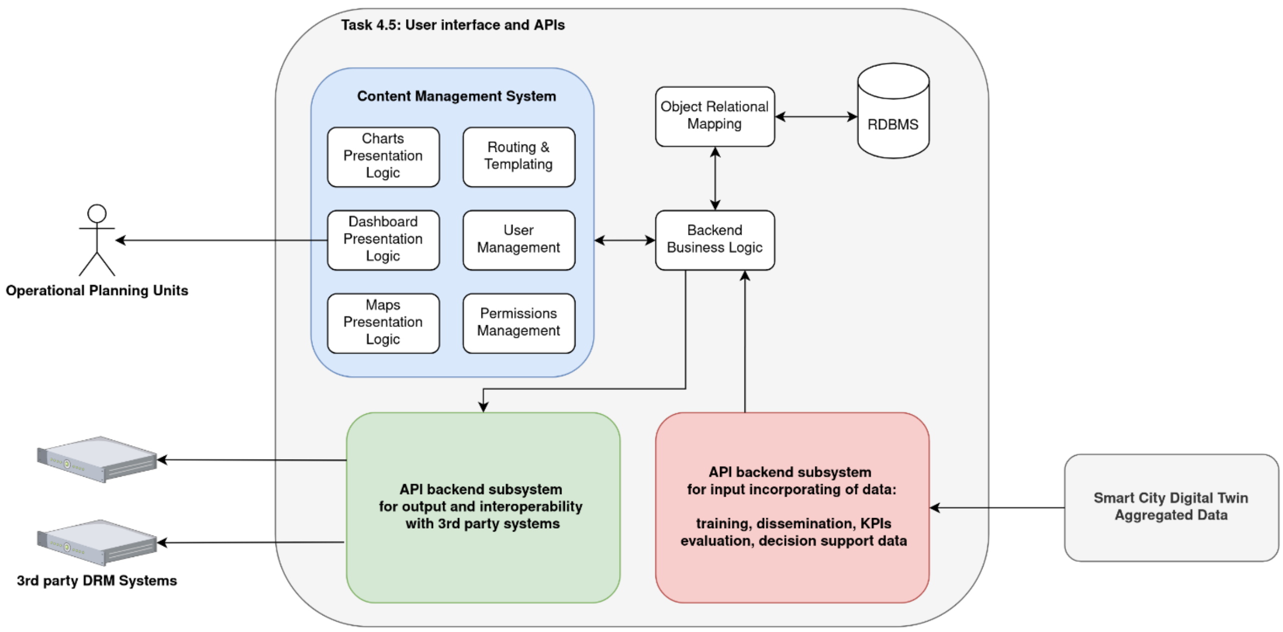

Figure 16 – PANTHEON UI architecture.

The proposed architecture of the User Interface of PANTHEON project is shown in Figure 16 and it consists of the next parts:

The most central part of the proposed architecture is its Business Logic module, which is a backend component responsible for orchestrating and coordinating all the other submodules of the UI platform, both those responsible for the visual representation and the human interaction with the system, as well as the backend modules responsible for handling the data flow and aggregation when necessary and those responsible for local data storage and communicating with other systems. The business logic submodule is also facilitated in its operation by the object relational mapping tool, which manages the transformation of the relational tabular data stored in the database system to a more abstract object-based data model getting them translated to the SCDT data domain that the end user expects to receive by operating the Pantheon UI platform.

The visual representation and human interaction submodules form the content management system group. This subsystem is responsible for all aspects concerning data shown to the end user and input data that the user feeds back to the content management system to navigate and request different SCDT views or customized data transformations. The navigational aspect is handled by the routing and templating submodule, responsible for handling all Web URL paths and HTML templates that are processed in real-time for presenting the SCDT aggregated data to the end user. The user management submodule is responsible for managing the different users and roles of the content management system, the creation of new users or the updates and deletes of current users, as well as the Web-based authentication and authorization mechanisms. The permissions management submodule operates in accordance with the routing and user management submodules to control each end user's access permissions, either allowing or denying access. On the frontier of the content management system, the end user interacts with three different submodules responsible for proper data presentation, accordingly with the specific desired data batch required for viewing. The dashboard submodule plays a semi-central part as the user's navigation is directed either to the submodule responsible for chart rendering or the submodule responsible for the visualization of the geographical-related and GIS data batches. The content management system as a group communicates with the backend business logic module to request specific objects stored in the database system, or static and real-time data flows that originate from the SCDT aggregated data. The business logic module is responsible for discovering and deciding where each data source should reside and which other submodule it has to trigger for getting the appropriate data batch that the end user originally requested via the CMS.

Considering the data feed that the proposed architecture of the User Interface of the PANTHEON project handles, the task is divided into two separate subsystems, one for data output and one for data input. The data input submodule operates on the aggregated data that the Pantheon project has produced for the smart city digital twin representation. This includes all aggregated raw data feeds, training, and dissemination data, as well as produced KPIs, evaluation and decision support data produced by the other informational systems of the Pantheon Project. The data input submodule provides an API that the other systems can consume to either directly transfer data feeds to the UI platform (when necessary) or inform the UI platform about the exact network-based location of the data feeds, for example an API-based location, a database, or an external resource. The data input submodule receives all requests and incoming data and informs the central business logic submodule to decide and plan on how the UI platform will hold the data feed information and metadata, either consuming the whole feed and storing it in the database system, or by storing an appropriate link for real-time fetching it when necessary. In a similar manner, the data output submodule provides a different

API that external disaster risk management systems can consume to request specific data resources and feeds. In such cases, the data output submodule forwards the request to the business logic submodule, which is responsible to query the other backend submodules to properly fetch what is necessary for the DRM external request to be successfully served.

9.1.1 UI FRAMEWORKS

Considering the overview of the UI architecture of the PANTHEON project, as presented above, it is apparent that the front-end framework of such a complex system has to be implemented by synthesizing a collection of various open-source and customized technology solutions, libraries and frameworks in order to reach the desired outcome of digitally representing virtual data contexts that faithfully mirror real and simulated city conditions and forming a SCDT representation. As such, the proposal includes several well-known and recognizable technology recommendations that facilitate the proposed UI platform implementation and provide the necessary efficiency, scalability, and customization for the realization of such complex user interfaces. These technologies are primarily indicative according to the common software engineering knowledge, but can be accompanied in the future by specialized customizations implemented specifically for the PANTHEON project and its broader goals:

- **React**: A JavaScript library developed by Meta (known for Facebook) for building user interfaces, React enables developers to create interactive UI components and manage the application state efficiently. It is widely used for creating single-page applications and complex user interfaces.
- **AngularJS/Angular**: Developed by Google, Angular is a TypeScript-based open-source web application framework used for building dynamic, single-page web applications. It provides a robust architecture for creating scalable and maintainable user interfaces.
- **Vue.js**: A progressive JavaScript framework for building user interfaces, Vue.js is known for its simplicity and flexibility. It is often used to develop single-page applications and is designed to be incrementally adoptable.
- **jQuery**: Although not a framework, jQuery is a fast, small, and feature-rich JavaScript library used for event handling, animations, and Ajax interactions. It simplifies the process of creating interactive user interfaces and is compatible with various browsers.
- **Bootstrap**: A popular open-source front-end framework that simplifies the process of designing responsive and mobile-first websites and web applications. It provides a collection of tools, templates, and reusable components, making it easier for developers to create modern and visually appealing user interfaces. Bootstrap is widely used by developers and web designers worldwide for its simplicity, flexibility, and extensive set of features, making it a valuable tool for creating responsive and visually appealing user interfaces for a wide range of web applications and projects.

These open-source user interface architectures can provide the PANTHEON project developers, implementors and system integrators with an initial collection of necessary tools and frameworks to build and create scaffolded wireframes, prototypes and finalized solutions for the wide range of the PANTHEON project needs and goals.

9.2 USER INTERFACE COMPONENTS AND FUNCTIONALITIES

In a similar manner to the proposed UI frameworks approach, as presented above, building, and developing the user interface architecture and platform for the SCDT representation requires incorporating a variety of components and functionalities to ensure seamless and successful interaction among the components proposed for the finalized UI PANTHEON platform. The proposed functionalities that the PANTHEON UI platform should support are as follows:

- **Real-Time Data Visualization**: Displaying real-time data from various sensors and sources, such as traffic flow, and infrastructure status, using interactive charts, graphs, and maps, is a core functionality of the Pantheon goals, as it provides the insights of the SCDT model in a clear manner.
- **Geospatial Mapping**: Integrating interactive maps to provide a visual representation of the PANTHEON project modelled cities, is also an integral part of the proposal, as it will allow the end users to explore different areas and view specific data points and events within the digital twin representation.
- **Sensor Data Integration**: In a similar manner, integrating data from In-situ IoT sensors, cameras, and other monitoring devices, will allow the PANTHEON stakeholders to access and analyze data related to various aspects of the cities' infrastructures and services.
- **2D Visualization and Simulation**: The geospatial mapping integration proposal can be supplemented by incorporating 2D top-down map visualizations and simulation capabilities for providing more comprehensive views of the PANTHEON cities' infrastructures, enabling end users to simulate scenarios and assess the impact of potential changes or developments.
- **Customizable Dashboards**: Creating customizable dashboards that allow the PANTHEON end users to personalize their interface and display specific data points, events, and analytics relevant to their roles and responsibilities within the SCDT ecosystem, should offer added value to proposed UI architecture.
- **Predictive Analytics**: Integrating predictive analytics tools to forecast future potential risks, performance indicators and KPIs based on historical data, real-time inputs, and data feeds of the PANTHEON systems, should enable city planners to make informed decisions or accurate simulations according to the goals of the project.
- **Data Filtering and Analysis Tools**: Providing data filtering and analysis tools that enable the PANTHEON end users to sort, filter, and analyze the project's large datasets, is also an important aspect of allowing the project to extract meaningful insights and identify patterns within the data.
- **Security and Access Controls**: Implementing robust security measures and access controls, should be an important priority for the PANTHEON project as to ensure the privacy and integrity of sensitive data, allowing only authorized end users to access specific information based on their roles and permissions.
- **Historical Data Access**: Enabling access to historical data is another aspect that could potentially provide added value for the PANTHEON project, by allowing the end users to analyze past indicators, identify long-term patterns, and assess the effectiveness of previous risk management strategies.

- **Integration with 3rd party DRM Systems**: Lastly, another PANTHEON requirement is to facilitate seamless integration with external disaster risk management systems, enabling data exchange and interoperability with other SCDT platforms, services, and tools.

The above proposed user interface functionalities originate from the analyzed requirements of the PANTHEON projects and from meaningful relevant SCDT aspects that can potentially be beneficial for the objectives and needs of the project. They can provide the PANTHEON stakeholders with the necessary tools and insights to manage and optimize various aspects of urban infrastructure, services, and sustainability initiatives.

10. 2D VIRTUAL REPRESENTATION TRAINING TOOL

10.1 PANTHEON VIRTUAL REPRESENTATION TRAINING CONCEPTS

In Crisis Management, many different situations and events, which can have various impacts on the population and infrastructures, must be taken into account. With respect to each specific case, the sequence of events will involve critical temporal aspects, the spread over long or short duration of the effects of the crisis could generate specific difficulties in terms of actions to be taken to counter them, especially at the very first moment of the raise of the crisis.

These constraints require, to guarantee the effectiveness of the rescue teams during the different phases of the crisis, to use priority management tools, which are part of the objectives of the PANTHEON project. Some of these tools concern the upstream preparation of teams with the objective to learn them appropriate reflexes and processes, aiming to improve the duration of rescue operations and optimizing the use of available resources. It is also a question of limiting the confusion inherent in the first moments of the raising of the crisis, and of improving communication channels by giving the different actors a broader view than the one linked to their own contribution. these aspects are made more complex by the fact that the crises considered within the framework of this project can be extended to the scale of a city or region and could involve many various stakeholders.

When it comes to management, a general principle is to make sure that important matters are dealt with before dealing with urgent matters. The essence of this approach is to limit the number of items that can become urgent, and to avoid becoming locked into a continuous management of a crisis situation characterized by a large number of emergencies to be dealt with, and therefore in a confused situation that can become chaotic. While this may seem a strange precept in the context of crisis management, which is necessarily characterized by a high number of emergencies to be dealt with, the idea remains interesting if we imagine that it is possible to anticipate and identify these emergencies upstream, before the crisis occurs, and to establish management plans that enable a large proportion of them to be maintained at the level of important items to be dealt with, without allowing them to reach the status of urgent items requiring a rapid, improvised response, and therefore characterized by a lower level of efficiency.

These principles will therefore always be borne in mind when defining the concepts and principles that will be used to describe the future learning and training tools developed as part of PANTHEON.

In practice, this leads to a series of high-level requirements and proposed functionalities that must be taken into account when developing the training solution:

- **Management of the georeferenced variables:** The tool must be able to represent, clearly and without ambiguity, data and information that are linked to very large surface linked to big urban areas or regional areas crisis. The purpose is to propose a wide and synthetic overview of the situation, and to provide accurate and easy to understand localization information.
- **Management of the temporal variable:** The tool must be able to simulate the temporal evolution of the crisis, to identify the time scales of the different phases and points of attention making up the crisis as a whole, to facilitate the definition of a scale of priorities and a staggering of counter-measures.

Example: Floods have a relatively long-time scale, enabling rescue measures to be put in place progressively, but the immersion of electrical installations can lead to fires, which are characterized by a much faster time scale, requiring much more reactive measures.

- **Opportunity for stakeholders to interact and propose actions:** As part of a training process and the adjustment of procedures and roles for each stakeholder, it is important to enable them to simulate their decision-making and actions, in order to enable evaluation of the actions undertaken and learning by trial and error. In this context, the time variable is of particular interest, enabling us to play back the effects of these same actions, and to go back and test alternative proposals.

  Example: Tt may be quite straightforward to propose evacuation solutions based on local population densities and theoretical road network absorption rates, but over time the network may become saturated with refugees. The learning tool will enable us to develop evacuation solutions that are resilient throughout the crisis, not just at the beginning.

- **Factor correlation to highlight actual impacts:** The difficulty of understanding each specific situation stems partly from the combined effect of several factors which, locally, can influence each other and make the situation more difficult to understand and deal with. The learning tool will have to take this complexity into account by correlating geo-referenced and temporal variables and representing their final effects, which are ultimately the element needed to define the actions to be taken by rescue teams. This function will essentially be handled by the core PANTHEON system and by the backend integrated into the learning tool.

  Example: Assessment corridors might be easy to predict by linking population density mapping with theoretical transit rates for the mobility network, but the evolution of the crisis may result in certain axes being cut off, with refugee flows transferring to unaffected parts of the network, which could lead to confusion and congestion. The tool will therefore need to present this saturation rate as a function of time, to enable the teams in charge of evacuations to anticipate and adapt the evacuation plan as a function of time.

- **Modularity to enable continuous improvement of the tool:** The architecture of the learning tool will need to be simple and modular to ensure its future evolution and guarantee that it can consider new types of crises or an increasing number of parameters that can influence the learning and decision-making processes.

- **Synthetic, efficient and intuitive data presentation:** The tool must enable rescue teams to grasp major crises spread over areas that can reach regional dimensions, and that can extend over several days or even weeks. The graphical representation must therefore be designed to provide overviews that enable all essential parameters to be interpreted. The visualization will be oriented towards the Situational Picture concept, in that the objective is rapid understanding of a given situation, and towards the Common Operational Picture concept, in that the graphic representation should be usable by all types of stakeholders involved in crisis management processes and should enable each of them to quickly understand the issues and actions characterizing the involvement of the other players.

Example: In view of these objectives, and as a first step, a 2D visualization with specific functionalities is envisaged, but trade-offs still need to be carried out once the requirements and study cases of the PANTHEON project have been clarified.

- **Geo-referencing and temporal representation of information:** In the same vein as the previous point, data and information will need to be presented in such a way as to facilitate their spatial and temporal interpretation, since the main difficulty for relief teams in a major regional crisis is coordinating efforts and optimizing available resources. The representation should therefore enable the situation to be viewed as a whole, so that hot spots and mini-crises can be quickly identified within the macro-crisis framework.

  Example: In the event of a terrorist attack taking place at a specific point in an urban area, the transmission of information can quickly lead to panic and saturation of communication systems in places that may be far removed from the initial crisis. This can be the starting point for other secondary crises, such as uncontrolled crowd movements that can lead to personal injury. Eventually, the tool will have to integrate this notion of secondary crisis, to avoid aggravating the initial crisis through collateral effects.

- **Strong link with PANTHEON's main tool to ensure effective and relevant training:** As mentioned in previous deliverables, the course of a crisis and its management is structured around several phases, from upstream (Learning, setting up procedures…), during (emergency and medium-term management…) and downstream (Lesson Learned, reconstruction, preparation for the next crisis…). For reasons of efficiency, it is important that the tools used for the different phases are very similar. Learning tools, for example, should be identical in functionality and representation to actual emergency management tools. This will facilitate the instinctive reproduction of reflexes and procedures learned during the upstream phases. This requirement will be continually considered, through exchanges with the other WP members of the PANTHEON project, during the learning tool development phase.

In terms of integration into the main PANTHEON system (see Figure 17), the training tool to be developed as part of Task 4.5 will be directly linked to the core system via the transmission of pre-processed data and information. This will include all the geographical data and the results of risk analyses, statistical assessments, and artificial intelligence processing, which will be used to correlate and link together the raw data collected by the PANTHEON ecosystem.

This data and information will be transmitted to a Scenario Generator Backend, whose task will be to organize it spatially and temporally, and to format it so that it can be exploited via a graphical interface, enabling operators to test scenarios and identify priorities in the event of the occurrence of the crisis in question. A few processes and correlations will also be integrated into the Scenario Generator Backend to take into account the actions proposed by operators via the visual interface, and to render the effects of these actions.

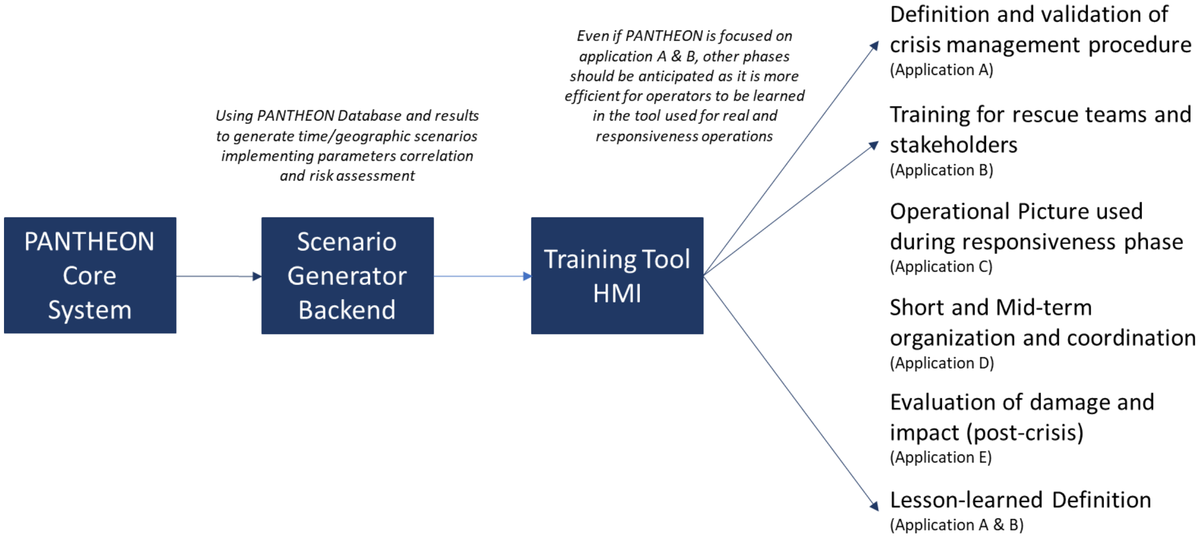

Figure 17 – Training tool integration in PANTHEON Core System.

This architecture is described in detail in the next chapter.

10.2 PANTHEON 2D VIRTUAL REPRESENTATION TRAINING TOOL ARCHITECTURE AND DESIGN

Based on the high-level requirements established in the previous chapter, the most suitable architecture for the visualization part of the learning tool will be based on a layer representation integrating all the information. This multi-layer architecture is shown in Figure 18, with the layers grouped into different levels:

- **Geographical information** itself, which comes from a variety of sources and needs to be updated as required, but on a relatively slow timescale. It mainly contains visual elements enabling operators to find their way around and identify reference points and may also include topographical information
- **Static information** specific to infrastructures, communities, demographic data... or any other data enriching geographic data and the interpretation operators may have of it. These data need to be refreshed more frequently than geographic data
- **Information relating to the crisis under study**, including the results of correlations and analyses carried out as part of PANTHEON's main application, and specifically in relation to simulated crises and their impact on communities and infrastructures. The rate of refreshment is even more frequent, as each modification is the result of a combination of several factors
- **Dynamic information** directly generated as a result of the analysis of the impact of the actions proposed by operators on the parameters specific to the crisis. The refresh rate is instantaneous, depending of interaction of the operator with the HMI

In addition, the visual interface will include a temporal trigger to simulate scenarios, assess the beneficial effect or otherwise of proposed actions, and enable operators to move around in time to better grasp the temporal aspect of the unfolding of the crisis, and identify the sequence of priorities to be addressed.

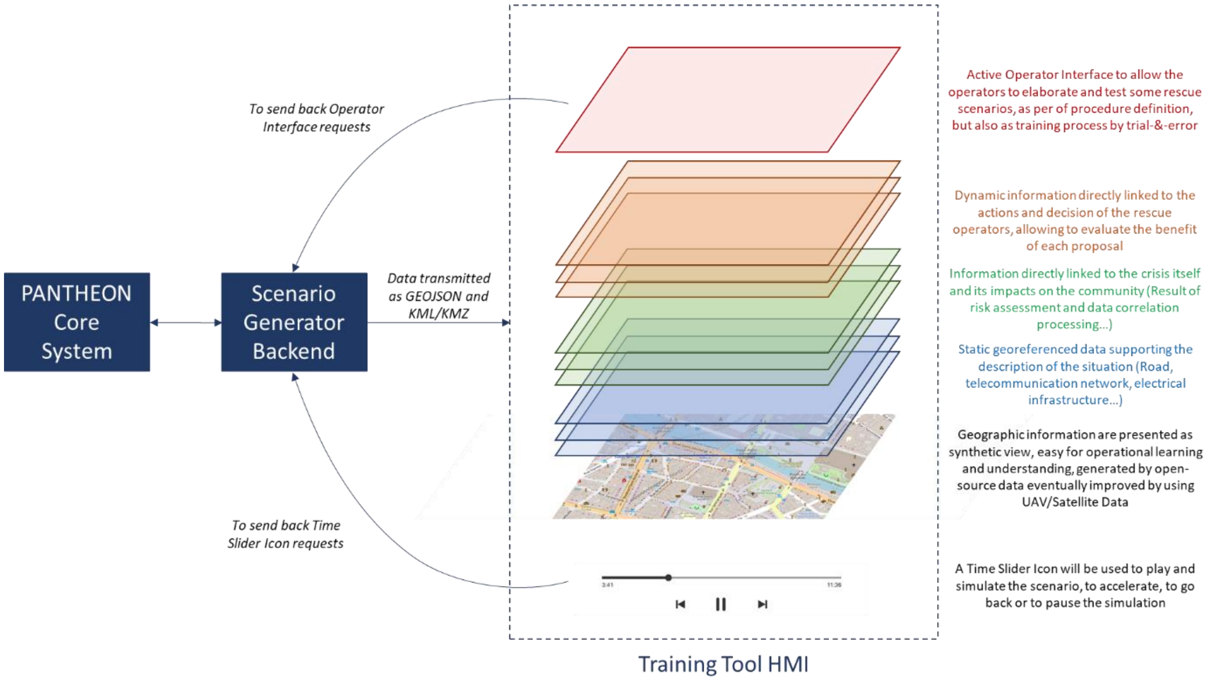

Figure 18 – Overview of PANTHEON training tool preliminary architecture.

In addition, a series of functionalities will be offered to operators, enabling them to activate or deactivate the various layers, with the aim of clarifying the visualization and improving the situation understanding and decision-making processes. These different layers can also be grouped together in contextual groups to assist the operator and further increase his level of situational awareness.

The following sections present a few case studies to illustrate the functionalities and added value envisaged.

Case study 1: Major flooding in an urban center

This will have to be clarified in the framework of other tasks of PANTHEON project, but as it is difficult, if not impossible, to channel water in an urban environment during major flooding. The main problems considered in this rough analysis is related to evacuating populations, supplying people taking refuge on floors and protecting critical infrastructures (i.e., electricity and telecommunications networks, hospitals, water supply systems, etc.).

Figure 19a) illustrates the evacuation plan initially drawn up in anticipation of rising water levels, with high-capacity routes chosen to move the maximum number of people in the shortest possible time. Figure 19b) shows the evolution of the situation, a function made possible by the integration of the time factor in the PANTHEON tool, showing that the chosen communication routes are eventually cut off by the rising waters. This can lead to problematic confusion, as people initially heading in one direction are forced to go back on their steps, creating congestion and confusion. The figure therefore identifies alternative communication routes that should be chosen from the outset or selected after a certain period of time that is known to all beforehand, in order to limit communication problems and the resulting confusion.

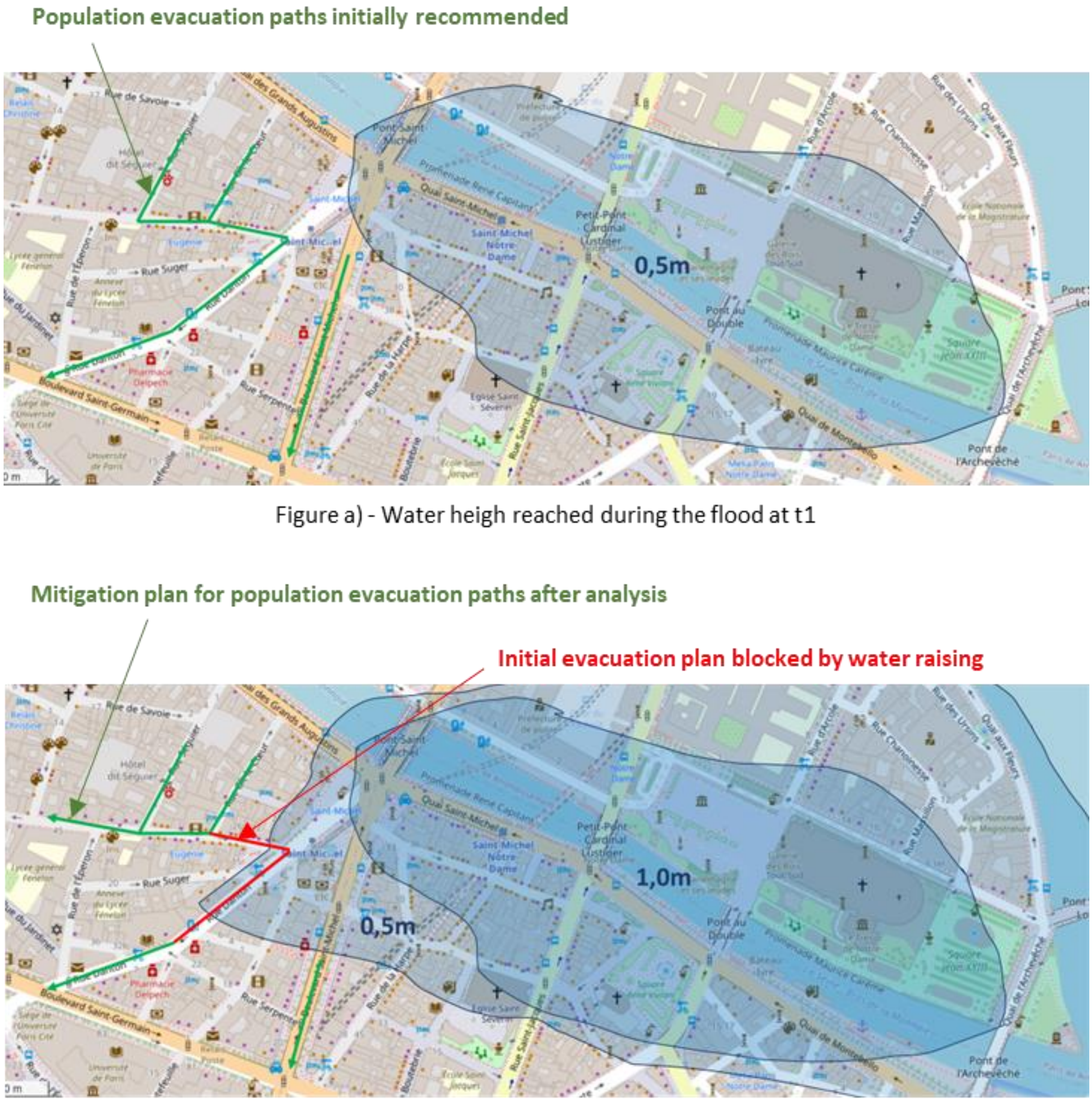

Figure a) - Water heigh reached during the flood at t1

Figure b) - Water heigh reached during the flood at t2

Figure 19 – Major flooding in an urban center, and impact on evacuation plans.

With respect to the supply of isolated populations within disaster zones, and therefore considering the problem related to access to the buildings in which they have taken refuge, the tool should enable to identify the safest and most efficient trajectories to be identified, depending on the effects of the crisis. Figure 20 gives the example of major flooding in an urban area, with a correlation, for example, with empirical charts characterizing travel difficulties as a function of water height or current speed. This makes it possible not only to define travel speeds, but also to deploy available vehicles efficiently, depending on the objectives set in advance (Zodiacs, boats with or without motors, rowing boats, etc.).

In terms of priority, urgency or criticality, this type of information can also be correlated with other data, such as demographic data, to anticipate the difficulties that will be encountered by operators. Figure 20, for example, shows a correlation with population density mapping, to help rescue teams planning the navigation equipment that will be needed according to the number of people to be rescued.

Figure 20 – Identification and analysis of rescue strategies based on the conditions imposed by the crisis.

Protection of the infrastructure can also be considered by anticipating the impact of the crisis on its integrity and establishing priorities. As an example, Figure 21 shows the mapping of the electrical network, and identifies the case of a main node submerged by the flood, with the effect on the local network. This type of problem is difficult to contain, but anticipating it will enable the operators to take measures aiming, for example, to isolate the affected nodes from the rest of the network, to establish a plan for the alternative supply of power and light to evacuees trapped in the area, or at the very least, to avoid fire outbreaks, which would be a cause for aggravating the crisis.

Figure b) - Impact of the flood on the electrical network

Figure a) - Location of electrical main dispatcher and related network

Figure 21 – Analysis of the impact of the crisis on critical infrastructures, to support the definition of associated mitigation plans.

Case study 2: Forest fires in hard-to-reach area

The second study case is unfortunately a classic one, as climate changes are leading to dramatic effects on forest fires, which in many countries are on the increase every year, both in terms of number of occurrences and intensity. The problems are manifold, but we are more specifically interested in the protection of fire-fighting teams, who sometimes have to operate in areas far from any infrastructure. The problem is therefore to plan escape routes to prevent personnel from being trapped by the flames.

The learning tool should enable operators to simulate the temporal spread of the fire as a function of a large number of parameters (meteorological, soil conditions, ambient humidity, type and condition of vegetation, etc.), so as to be able to anticipate the moment when it may be necessary to retreat, while delaying it as much as possible in order to leave themselves a chance of influencing the spread of the fire itself. Figure 22 illustrates this simple case, where the risk for teams is of being trapped on the banks of a river, the challenge being to prepare an escape route to the only bridge in the area.

Figure 22 – Simulation of fire propagation as a function of time and external parameters.

Case study 3: Extreme heatwave in an urban environment

Intense heatwave episodes tend to intensify, in terms of occurrence, duration and maximum temperature levels reached during the crisis. Their effects in urban areas can be devastating, as these areas are not very resilient to this type of climatic phenomenon due to the masses of building materials that capture and store heat.

Some populations are particularly sensitive, due to their age or pathologies. In addition, different parts of a city are not all in the same boat, due to the presence or absence of vegetation or waterways, or the presence of wind on certain more exposed roads.

Combining and correlating the different maps (temperature zones that can be reached and population density at risk) is a tool that should enable operators and rescue teams to better apprehend the effects of a crisis, and to anticipate by deploying specific resources in particularly sensitive areas. This case study is shown in Figure 23, which identifies, for example, two areas where certain rescue systems can be concentrated.

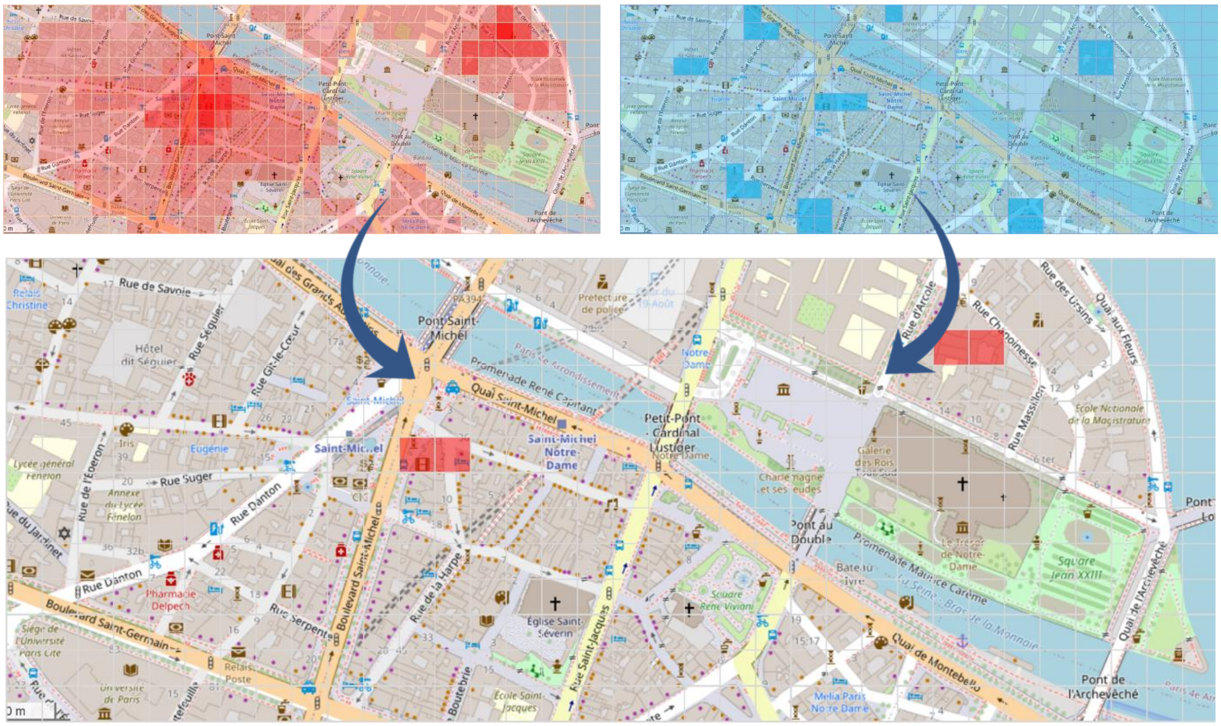

Figure 23 – Identifying areas to monitor during intense heatwaves.

As a conclusion, the initial and preliminary concept of architecture for the PANTHEON Training Tool will be based on a multi-layer visualization interface connected to a Learning Tool background, their integration allowing to play and simulated rescue scenarios. This tool will be focused on the ability for the learning rescue teams to propose some mitigation plan, and to assess the pro and cons for each proposal. With this principle, this allows a learning implying a virtual trial-and-error strategy.

11. THIRD-PARTY DRM PLATFORMS

PANTHEON's SCDT will also integrate and establish communication with 3rd party DRM platforms, available at the pilots' sites, to obtain as much information as possible in the process of decision-making and risk management before the disaster event occurs. Thus, the DRM and decision-making process in the framework of PANTHEON will be supported by external platforms, offering their insights, decisions and risk management approach and processes with respect to the PANTHEON SCDT and its outcomes.

For the integration of PANTHEON SCDT with the pilot's third-party DRM platforms, a comprehensive analysis of the HPOL and JOAFG's internal systems will be conducted to identify specific requirements for data availability, communication protocols, and functionalities crucial for disaster management. A robust data interoperability framework based on international standards, such as OGC standards[90], and protocols (JSON, XML) should be developed to facilitate seamless data exchange, ensuring compatibility with the systems used by HPOL and JOAFG. Real-time data from the Digital Twin, encompassing infrastructure status, environmental conditions, and community dynamics, should be integrated. Data mapping mechanisms should be implemented to align Digital Twin data structures with those utilized by the DRM Operator Systems. Open APIs should be designed and implemented (such as OpenAPI[91] and AsyncAPI[92]) based on best practices (e.g., REST[93]) and asynchronous data exchange mechanisms (e.g. MQTT[94]) to establish communication channels between the Community-based SCDT and the DRM Operator Systems, ensuring secure and authenticated access to data and functionalities. Real-time data integration may involve establishing connections with HPOL and JOAFG internal data sources to incorporate real-time data related to e.g., law enforcement activities, medical facilities, and resources. The SCDT will be utilized for simulating disaster scenarios, incorporating data from HPOL and JOAFG for realistic and data-driven simulations to evaluate the effectiveness of data exchange and decision-making processes. These models will be validated and refined based on historical data and input from DRM operators. Simulation exercises will be conducted to test the interoperability and responsiveness of the integrated systems. Collaborative decision support tools will be implemented within the PANTHEON SCDT to enable real-time communication with HPOL and JOAFG, fostering shared situational awareness and coordinated responses during disasters. Relevant features that could be implemented include decision support for resource allocation, task assignment, and incident tracking. Training sessions will be provided for HPOL and JOAFG personnel using the integrated SCDT platform, promoting continuous learning and adaptation to the new disaster management ecosystem. Monitoring mechanisms will be implemented to track system performance and data accuracy, establishing feedback loops for continuous improvement based on user experiences and evolving disaster management needs.

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[91] https://www.openapis.org
[92] https://www.asyncapi.com
[93] Fielding, Roy Thomas (2000). "Chapter 5: Representational State Transfer (REST)". Architectural Styles and the Design of Network-based Software Architectures (Ph.D.). University of California, Irvine.
[94] https://mqtt.org

12. CONCLUSIONS

This deliverable provided a detailed description of the PANTHEON SCDT model that will be developed in the course of the project and will constitute the basis for the architectural design of the complete PANTHEON platform and system. The individual constituent building blocks were thoroughly presented, including their basic technical, operational and functional characteristics, that they will be utilized in the framework of the SCDT and for the project purposes.

The SCDT includes all the necessary and relevant information to precisely model and digitally represent the area of interest, the disaster and the foreseen impacts. This information includes in-situ, aerial and satellite data for the accurate representation of the area, its infrastructure and its environmental/weather conditions. Since PANTHEON will develop a community-based DRM approach, the SCDT model also includes valuable information regarding the affected community and its specific characteristics.

AI-supported simulations will take place to extract valuable information for the disaster impacts that will consequently assist the decision-making process of the AI-based DSS. In that sense, the relevant end-users and stakeholders will be able to exploit the outcomes of an advanced tool for the actions to be taken and the risks to be managed, especially before the disaster occurs. A training tool is also included and described, which will assist end-user groups such as first responders to optimally evaluate and plan their actions before, during and after the catastrophic event.

Finally, the SCDT model constitutes the foundation for all the technological developments in the PANTHEON system architecture. This deliverable, despite its detailed description of the model, does not provide in-depth technical analysis of the system and its components, rather it preserves a high-level definition of it, since a deeper technical analysis will follow in forthcoming deliverables, such as D3.7.

13. LIST OF ABBREVIATIONS

Abbreviation	Meaning
AI	Artificial Intelligence
API	Application Programming Interface
CAD	Computer-aided Design
BIM	Building Information Modelling
CBDRM	Community-Based Disaster Risk Management
DRM	Disaster Risk Management
DRR	Disaster Risk Reduction
DSS	Decision Support System
EMS	Emergency Management Service
ETSI	European Telecommunications Standard Institute
GDPR	General Data Protection Regulation
GIS	Geographic Information System
HTML	HyperText Markup Language
HTTP	HyperText Transfer Protocol
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IoT	Internet of Things
ISO	International Organization for Standardization
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union Telecommunication Standardization Sector
JSON	JavaScript Object Notation
KPI	Key Performance Indicator

MBSE	Model-Based Systems Engineering
ML	Machine-Learning
NGSI	Next Generation Service Interfaces
SAR	Synthetic Aperture Radar
SCDT	Smart City Digital Twin
SDCT	System Dynamics-based Computational Thinking
UAV	Unmanned Aerial Vehicle
URL	Uniform Resource Locator
WP	Work Package

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