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Original Scientific Article

DIGITAL TWINS FOR SMART CITIES: POSSIBLE APPLICATIONS IN THE CASE OF MUNICIPALITY OF TRIKALA

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Abstract: Digital twins have received increased popularity in the last decade thanks to the numerous advancements in various scientific fields of software and hardware. The latest achievements in sensors, actuators, internet of things, machine learning, artificial intelligence, data storage and management have improved significantly the efficiency of their application in several sectors (including manufacturing, aerospace, healthcare, infrastructures, vehicles, supply chain and logistics etc.) with partially different characteristics. One of these fields that receives a lot of interest from various research groups is smart cities. Smart cities are urban areas that make use of the latest technologies and of available data sources (in most cases in real time) to improve the living conditions of the citizens and manage efficiently and safely the available public resources, data and infrastructures. The main goal of this chapter is to make an introductory presentation of the most important features related to the two main terms according to the literature, to describe the statuses of them and to present certain goals for the upcoming years. Finally, an attempt to evaluate how realistic and prompt

such an implementation can be in city of Trikala Greece will be attempted with respect to the maturity levels of specific digital twins' applications.

Key words: *digital twins, smart cities, Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning, sensors and data management, urban infrastructure, Industry 4.0, Trikala.*

RELATIVE LITERATURE

Digital Twins

Mirrored systems, as a precursor to digital twins, can be traced back to NASA's Apollo program. NASA engineers built sophisticated, physical replicas on Earth to manage spacecraft in deep space. Their main intention was to continuously monitor the status of the Apollo missions, as well as to simulate problems that appeared in real-time and apply and evaluate possible solutions. Historically, the term digital twins (DTs) was introduced in 2002 by Michael Grieves, at University of Michigan executive course on product lifecycle management (PLM). Dr Grieves proposed a model consisting of 3 main elements, the physical product, the digital product and the bidirectional connection between them for flow of data and information [1]. The term digital twins, however, received increased interest in the scientific community in the latest 6-7 years, as several related technologies and fields that enable the implementation of operational and efficient Digital Twins has taken place. Such fields include, but are not limited to, Industry 4.0, Internet of Things, Analytics, Big Data, Cloud Computing, Artificial Intelligence and Machine Learning, Sensors and Actuators. Several authors have tried to describe formally Digital twins. Some of the most popular DTs definitions are presented in [2], [3]. DTs can be defined as (physical and/or virtual) computer-based models that are simulating, emulating, mirroring or "twinning" the life of a physical entity, which may be an object, a process, a service, a human or a human-related feature. Another definition considers DTs as digital representations of physical products, systems or processes used to simulate, analyze, test and evaluate strategies or features before they are implemented. Some terms that are met in literature with similar meaning with DTs include cyber physical systems (CPS), Digital Shadows, Digital Threads and Digital Replicas.

The main difference between DTs and traditional models is that models are not anymore static, as they can provide a dynamic image of the system's behavior in real time. DTs consist of the real system and the model that mirrors its behavior using appropriate technologies and tools that enable the bidirectional communication between physical system and model. Sensors signals are sent from real system to the model, while the model actuates strategies, decisions and activities, taking advantage of modern tools and methods (such as machine learning and artificial intelligence).

A graphical representation of this concept in the case of an oil refinery is shown in Figure 1.

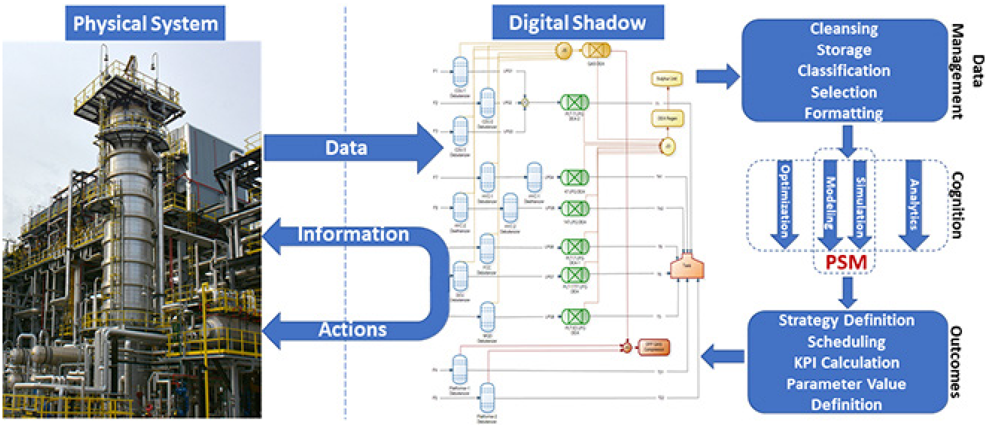

Figure 1: Physical system - digital shadow communication and services interoperation [4]

As will be made clear in upcoming sessions, literature concerning DTs increases every year. Many publications are rather theoretical and only few present totally or partially implemented applications. Some of the fields that receive increased interest include manufacturing, aerospace, healthcare, infrastructures, vehicles and Supply chain and Logistics as shown in Figure 2. Indicative surveys and reviews on DTs applications include [5], that presents a survey of Digital Twin techniques in smart manufacturing and management of energy applications, [6], that refers to a systematic review regarding Digital Twins in healthcare IoT, [7] and [8] that survey publications on digital twin-assisted intelligent vehicle localization and DTs for Internet of Vehicles respectively, while [9] presents a survey on the latest DT applications in Aerospace. All surveys and reviews on applications of DTs in specific fields categorize with different criteria the referred publications and present the current state of the field, opportunities, limitations and barriers, tools methods and open issues, challenges and future steps where researchers should focus. A lot of work is also done in the field of standardization and semantic modelling of DTs [10], as the need for common frameworks guidelines and protocols is crucial. General standards for DTs such as ISO/IEC 30173 as well as Industry specific standards such as ISO 23247 for manufacturing industry and ISO/IEC JTC 1, SC 41 that focuses on security and interoperability are under development.

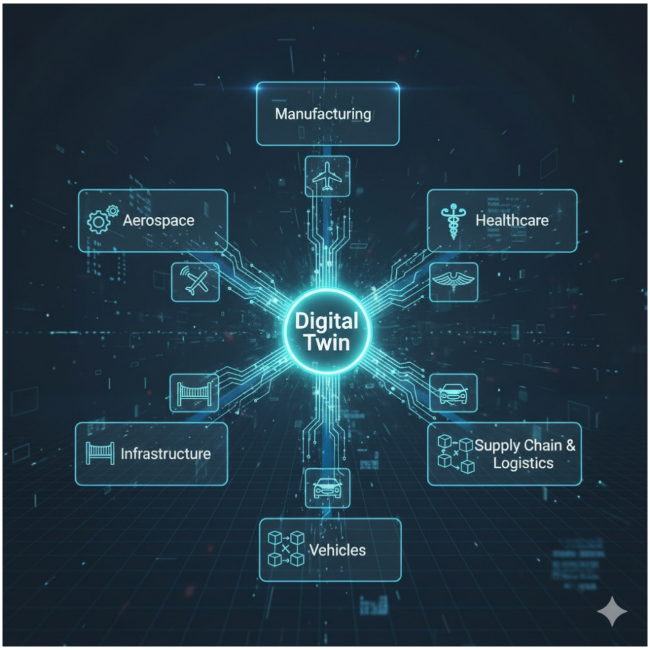

Figure 2. Digital Twins application fields

Smart Cities

The term Smart City is used to describe an urban area that utilizes an extended network of interacting digital technologies (both hardware and software) and different sources and types of data to improve the efficiency of city services and operations, enhance the well-being and safety of its residents and promote environmental sustainability.

While the idea of using technology for urban management applications can be traced back to post-World War II, the term "smart city" began to arise in the 1990s with the explosion of the internet and digital services. At that time the available solutions were rather trivial and with limited capabilities and only several years later the smart city concept was formed as part of the "Smarter Planet" campaign, announced by IBM in 2009. The main idea of this concept was to make possible the transformation of world's systems so that they could become more "instrumented, interconnected, and intelligent." This shift moved the focus from simply providing digital services to integrating technology directly into a city's physical infrastructure, using sensors and data analytics to optimize resources availability and consumption and providing advanced efficiency and intelligent solutions to smart city's residents.

As in the case of DTs, several definitions of smart cities can be met in literature. Different authors focus on different insights and features of smart cities and present their own formal description. Introductory surveys in smart cities can be found in [11] and [12]. According to [11], a smart city is the one that manages such developments by excelling in multiple key sectors such as economy, mobility, environment, people, living and government". According to [12] ,Smart cities use digital technologies, communication technologies and data analytics to create an efficient and effective service environment that improves urban quality of life and promotes sustainability. From both definitions presented above, technology, human and institutional factors are the core components of a smart city. Terms with similar meaning to Smart Cities are Intelligent Cities, Wired Cities and Digital Cities.

Figure 3. Smart City (AI-generated)

All surveys and reviews on smart cities categorize the respective publications with reference to different defined criteria and present current state of the field, opportunities, limitations and barriers, tools methods and open issues, challenges and future steps. Several standards related to smart cities are under development, with most important ISO 37101 that provides a management system framework for sustainable development in communities, ISO 37120 for urban indicators used to measure city services and quality of life, ISO 37122, that provides specifically indicators for smart cities, ISO 37123, which focuses on indicators for "resilient cities" and IEEE P2784 providing a framework that outlines the technologies and processes for planning a smart city [13].

For the implementation of Smart Cities concept, it is necessary to use extended networks of sensors for signals records and the processing of the received data in association with models of the critical infrastructures. The data received are then processed according to the needs of Decision-Making process and then evaluated (through what if alternative scenario simulations), for the selection and calculation of the best possible practices and strategies, anomaly detection, optimal resource management and forecasting. Zurich [14], Oslo, Singapore [15] and Canberra are some of the leading cities in this field and have applied certain solutions to their infrastructure. In [14], Zurich, Oslo and Singapore are compared with respect to indicators such as their sustainability strategies, environmental footprints, energy impact, waste management and air quality and crucial conclusions concerning their current statuses and future targets as well as the possible gains for the residents and city administrators.

Application of Digital Twins in Smart Cities

The initial motivation for studying the application of Digital Twins in Smart Cities was the fact that both terms (digital twins and smart cities) have become so popular in the last two decades due to the development of technologies and tools this period that enabled their implementation and improved their efficiency and evaluation accuracy. This can be justified by the significantly increased number of publications related to both these terms, as shown in Figures 4 and 5. From these, we can see that according to Scopus, the number of publications related to Digital Twins has increased from 136 in 2016 to 10.336 in 2024 (the respective number is 7.618 for 2025 till September) and the number of publications on Smart Cities has increased from 2.586 in 2016 to 8.644 in 2024 (the respective number of publications is 5.946 till September 2025). From the above numbers, it is obvious that both fields receive increased interest from several research teams and the application of DTs in Smart Cities is of high interest.

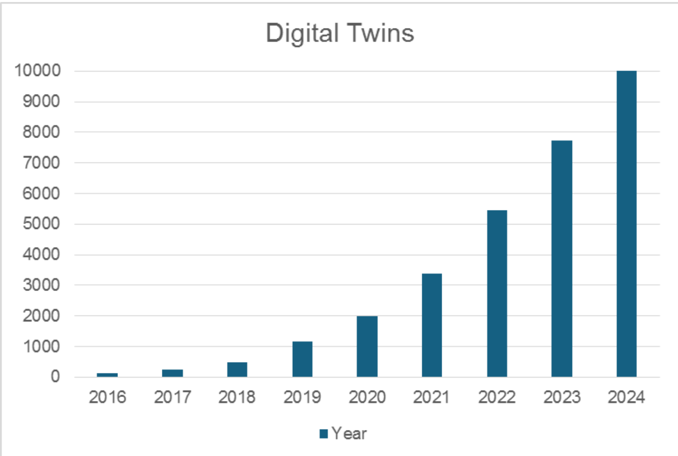

Figure 4. Number of Publications for Digital Twins in Scopus per year

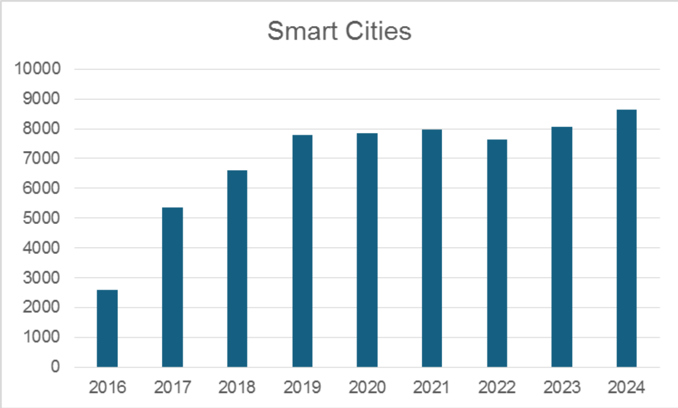

Figure 5. Number of Publications for Smart Cities in Scopus per year

Next step was to search for the publications referring to the combination of the terms Digital Twins and Smart Cities. As presented in Figure 6, the number of publications on this topic has grown dramatically, from just one paper on 2016 to 438 in 2024 (and 330 until September 2025) showing a close relation between the two terms. Figure 8 presents the bibliometric map for the combination of the two terms, produced using VOSviewer software. From this, we can see that the main items are: IoT, machine learning, sustainable development, information management and artificial intelligence.

An extra reason for this dramatic increase may be the Agenda for Sustainable Development (Agenda 2030) [16] adopted by all United Nations (UN) members in 2015. This Agenda created 17 world Sustainable Development Goals (SDGs that aim "peace and prosperity for people and the planet". The application of the Digital Twins concept in different fields of Smart Cities may lead to this direction, as it may leverage technology to create more intelligent, responsive and sustainable urban environments that improve the quality of life for all citizens. A review on Digital Twin technologies in Smart Cities, where authors group relative publications, can be found in [17].

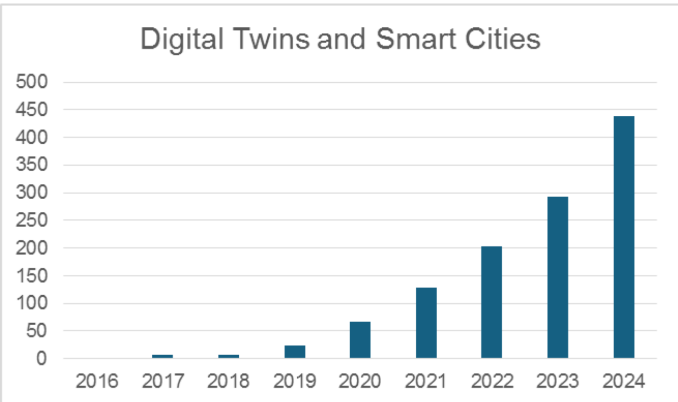

Figure 6. Number of Publications for Digital Twins Smart Cities in Scopus per year

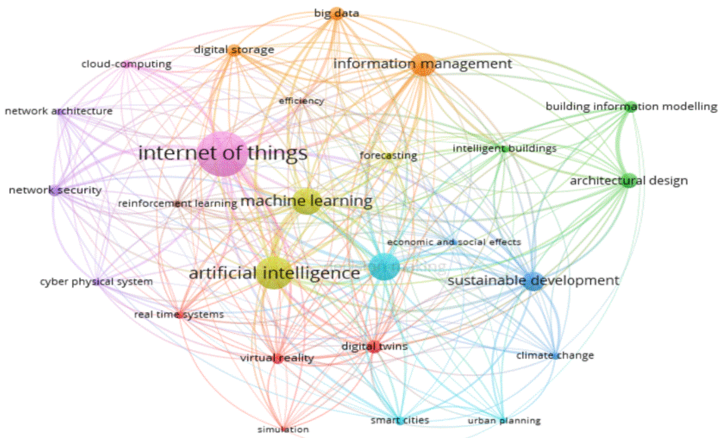

Figure 7. Bibliometric map for Digital Twins and Smart Cities

Some of the most popular applications of DTs in the field of smart cities, as shown in Figure 8, include the following:

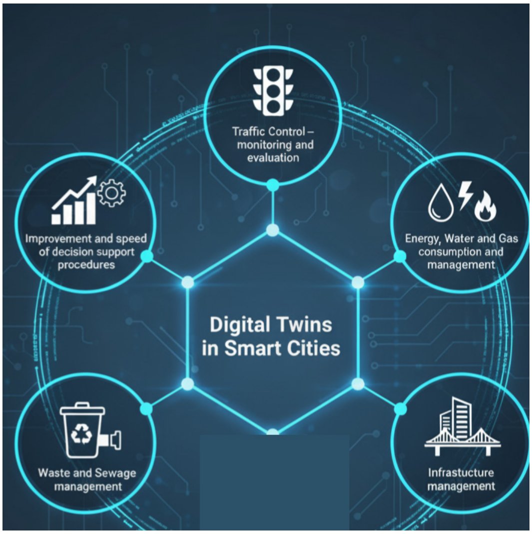

Figure 8. Applications of Digital Twins in Smart Cities

1. Traffic Control – monitoring and evaluation of traffic in real time and dynamic traffic lights control. Digital twins enable the development of a dynamic, real-time virtual replica of a city's main transportation network. This digital twin can be used to monitor traffic as well as to change certain parameters (for example duration of red lights) according to collected data, and because of certain events to improve traffic management and reduce

queues in the roads. In addition, it can be used to evaluate in real time alternative traffic control strategies and enable the best one.

2. Energy, gas and water consumption and management. The development of a virtual, real-time model of a city's resource networks makes it possible to monitor, analyze, optimize consumption and make forecasts for the upcoming periods. This can lead to reduced waste of resources, lower costs, and increased sustainability through the determination and evaluation of more efficient dynamic data-based policies.
3. Infrastructure management such as bridges, roads and buildings. In this case, dynamic, virtual replicas of these assets can be used to reduce the consequences of events to detect abnormal situations to move from reactive maintenance to a proactive, that is more cost-conscious and extends the lifespan and the availability of critical infrastructures. In addition, this can lead to better management of human and material resources for the city, as the number and the criticality of unexpected events in its infrastructures will be reduced.
4. Waste and sewage production and management. This application category is like energy gas and water; there is, however, a major difference that has to do with the absence of networks, whose behavior will be monitored. In this case, some of the elements, which should be monitored, are the capacity and the status of the landfill, the vehicles, whose routing can be defined dynamically, etc. In addition, forecast methods can be used to predict the needs for routes, vehicles, equipment and humans with respect to seasonality and other factors.
5. Improvement and speed up of decision support procedures. Digital twins significantly accelerate and improve decision support procedures in smart cities by acting as a centralized, interactive platform for data and information (static and real time) concentration, processing, analysis, and visualization. All previous application categories include decision making and typical decisions may refer to simulation of what if scenarios for optimal policy definition and use of AI and machine learning tools for optimizing evaluating decisions and strategies on prediction and resource allocation problems.

A significant factor that should be considered while implementing such projects concerns cybersecurity issues with the most important ones concerning data security, threat detection and prevention, anomaly detection and data sharing. Vulnerabilities and disorders in critical infrastructures, city operation and services may have significant consequences for its residents [18].

THE MUNICIPALITY OF TRIKALA

Geography, history, administration and living

The city of Trikala is located in the northwestern part of Thessaly, the second in area and third in population out of the four prefectures of Thessaly. The prefecture of Trikala has an area of 3,367 km. (72% mountainous, 11% semi-mountainous and 17% lowland) and is surrounded on three sides by mountains. To the west, there is the mountain range of southern Pindos, which occupies a fairly large part of the prefecture. The main rivers of the prefecture are either tributaries of the Pinios or tributaries of the Acheloos (or Aspropotamos), the two major rivers that essentially originate from the very point at the northwestern end of the prefecture of Trikala. The climate is continental, with severe cold in winter and extremely hot summer. The average annual temperature is 16-17 °C in the lowlands and lower in the mountains. The economy is mainly based on agricultural production, while the breeding of animals, especially cattle, is also developed, which has given impetus to the development of large dairy industries in the region. Forest wealth is another important economic source for the prefecture and tourism and services have begun to play an important role, as in recent years the area has started to receive a large number of visitors all around the year [19].

The wider area of Trikala has been inhabited since prehistoric times and the first signs of life in the cave of Theopetra reach up to 49,000 BC. The city of Trikala is built on the ancient city of Trikka or Trikki, which was founded around the 3rd millennium BC. The city was an important center of antiquity, as the mythical Asclepius, who is believed to have been the king of the city, lived and worked there. The city was the capital of a kingdom during the Mycenaean era and as described by the geographer Strabo, later became the center of the state of Estiaiotis, which occupied approximately the current area of the prefecture of Trikala. At the beginning of the second millennium, the city was presented for the first time under its current name, Trikala. The city was finally conquered by the Ottomans in 1393 and after a prolonged period of decline it became an important center of cottage industry, with renowned wool textiles and leather products. It was also an important intellectual center, as for a large part of the Ottoman occupation (1543-1854) the School of Trikki (and later the Greek School) operated here. On August 23, 1881, with the Treaty of Constantinople, the city passed into Greek sovereignty, as did the rest of Thessaly and Epirus, and was definitively incorporated into Greece in 1898.

In the 20th century, Trikala played a key role in the agricultural mobilizations against the landlords and was the place of the foundation of the first Agricultural Cooperative in Greece, in 1906. Also, in the WW2 occupation period, Trikala was field of intensive action of the National Resistance. Moreover, it is estimated that about 60% of Greek folk songs were composed and lyricized by Trikala creators, while the city was the birthplace of a plethora of well-known performers of folk hits. This great artistic development of Trikala was due to the confluence of populations with different musical sounds from a multitude of different genres, as the city is a commercial hub, right in the middle of Greece.

The current form of the Municipality emerged in 2010 with the "Kallikratis" program, as an expansion of the original Municipality of Trikala by incorporating 7 regional municipalities occupying mountainous, semi-mountainous, lowland areas. It is divided into 8 Municipal Units and 32 Local Communities, which correspond to the pre-existing Municipalities and their municipal districts (the latter constituted autonomous communities and Municipalities, prior to the implementation of the "Kapodistrias" program in 1998). Today, the Municipality of Trikala has a population of about 82,000 inhabitants, in an area of 608.48 sq.km. and operates with 7 deputy mayors. It is estimated that the city has about 45,000 bicycles in an urban population of about 72,000 inhabitants. The country's largest population to bicycle ratio is explained by the city's flat geographical urban terrain. In addition, transportation both within the city of Trikala and between Trikala and neighboring villages and settlements is also served through bus lines, taxis and private vehicles. The Municipality of Trikala maintains relations with cities abroad, while it also participates in international city organizations. Finally, the Municipality of Trikala has been twinned with 10 cities abroad and one Greek city [20].

Digital transformation and innovation

Since the 2000s, the administrations of the city of Trikala have consistently followed the path towards digital transformation and in 2004 essentially became the first Intelligent City in Greece. At that time, the first municipal Free WiFi network in the country was created and followed by the establishment of e-trikala S.A., the executive arm of the Municipality of Trikala for the implementation of European innovation programs. Moreover, on the initiative of the Municipality of Trikala and e-trikala, CitiesNet Digital Cities of Central Greece S.A. was founded in 2009. Among the dozens of innovative programs implemented by e-trikala, e-health and electronic dialogue programs were initially introduced. The rest of these programs is the electric driverless bus (CityMObil2 program), the world's first one to move in real conditions of urban environment. The activity of e-trikala. has placed Trikala on the pan-European map, participating in the global pool of actions for the implementation of programs aimed at improving living conditions in cities. Moreover, the Municipality with projects amounting to approximately 82 million euros over the last five years (excluding those implemented by national resources) makes full use of European programs through e-trikala and other public limited companies (DEYAT S.A., Urban Development S.A.).

In addition to this activity, in 2016 the Municipality of Trikala launched the Smart Trikala initiative without the use of external funding. The aim of this was the productive and prolonged provision of innovative services to citizens, in contrast to the pilot and ephemeral implementation of innovation offered by participation in European programs. Relying on the support of the project from technological partners such as Cisco, Vodafone, Space Hellas, EGRITOS GROUP and others, the Municipality developed with the use of its own resources a set of digital services for service, access, monitoring, recording and management. The most characteristic examples of those that operate to this day are the citizen line and requests system "20000", the citizen's electronic transaction center, the Smart City control center, the applications of smart devices and the geographic information system (GIS).

Evaluating the city's existing experience in innovation and the implementation of digital solutions, it was included in the "Smart Cities" action implemented by the framework of the National Recovery and Resilience Plan "Greece 2.0" with funding from the European Union-NextGenerationEU. The Smart City Strategic Plan of the Municipality of Trikala and the related 6.9 million euros budgeted project with the distinctive title "RESTART mAI City", were designed in-house and aim to create an ecosystem of people and technical infrastructure, for the implementation and creation of smart city practices. The design goal of the ecosystem is to be able to offer and at the same time be fed inclusively by as large a set of local users as possible. The integrated supporting technical system, which is planned to be created by the end of 2025, is based on the combination of a set of vertical systems that attempt to support the citizen in the main aspects of his daily life, with several horizontal systems for unified management, interconnection and support of the implementation of smart city practices. Taking into consideration the challenges and needs of the city, the actions included in "RESTART mAI City" concern the groups of Mobility, Health & Social Care, Energy, Civil Protection & Environment, Water Resources, Waste Management, Economic Development & Construction, Participation, Connectivity and other Horizontal Systems [20].

Another important milestone is the selection of the Municipality of Trikala in 2020 in the European Mission for the 100 Climate Neutral and Smart Cities of Europe by 2030. Following the course that began with the participation of Trikala in the Covenant of Mayors for Climate and Energy in 2008, this integration aims to mobilize more specific goals and actions, making the "Green City" one of the three goals for Trikala in the coming years, along with the technology and resilience of the Municipality. The city of Trikala has started its green planning in order to zero its carbon footprint and aspiring to become one of the first Greek cities to commit to implementing a specific strategy towards climate neutrality, significantly improving the quality of life of citizens and creating the conditions for a sustainable city and an extroverted local economy. In addition, with the development and approval of the City Climate Contract (CCC), the Municipality of Trikala contributes to Europe's overall effort to achieve climate neutrality by 2050. The areas of intervention outlined in the Municipality of Trikala CCC include Energy Systems, Mobility and Transport, Waste Management and the Circular Economy, Green Infrastructure and Nature-Based Solutions, Buildings and Smart City Actions.

Use Cases Presentation

The following application cases concern some of the component systems of the "RESTART mAI City" project, which in the context of the proposed ecosystem have a vertical character. However, their philosophy is compatible with the prospective development of digital twins, either in their field of application or broader and more complex physical systems characterized by the combination of the behavior of individual systems. In any case, the design of the following systems foresees upscaling to digital twin support systems depending on the needs and capabilities that will emerge from their use. In favor to the latter and in supplement of the respective features described below, each system supporting software was specifically requested to comply with the following functional specifications [20], [21]:

- Tracking data through interactive maps (streetmaps or googlemaps) that depict the location of device locations
- Interactive control of an unlimited number of individual or grouped automations
- Configuration of smart rules for the creation of actions (automations) related to the configuration of irrigation and notifications
- Secure and classified user access using appropriate username/password
- Modular design that allows for selective attachment of services and applications, ensuring easy and cost-effective expansion and management
- Interoperability and interconnection with the horizontal smart city platforms via the usage of secure APIs.

Energy consumption in municipality buildings

The vertical energy consumption monitoring and management system was designed to provide real-time energy data collection, storage and analysis. The consumption of electricity and other resources per zone and line in selected municipal infrastructure will be measured and recorded through smart meters and sensors. The collection of information will be done by a centralized platform that allows for the viewing of reports, the management of alerts and the configuration of parameters for the optimization of energy efficiency. In addition, the system will be integrated with the existing information systems of the Municipality for integrated data management and analysis, as described in [20] and [21].

The system was designed to be characterized by generality and ease of application to all present and future types of municipal infrastructure. For this reason, four levels of functionality were described, depending on the needs and requirements of the 183 installations selected to be included in the "RESTART mAI City" project.

- Level A infrastructure: Basic consumption measurement and central temperature control.
- Level B infrastructure: Level A + Diesel tank occupancy, cooling and lighting control.
- Level C infrastructure: Level B + Zoned control and measurement per line.
- Level D infrastructure: Level C + More specific measurements and control per unit, including specializations.

The assignment of municipal infrastructures to Levels A to C was based on a categorization methodology of the selected infrastructures based on their location, area and use (see Table 1). In conjunction with the project budget and by following a cost-benefit selection strategy, this categorization led to the inclusion of 175 up to Level C installations for consumption monitor and management. Specifically for Level D infrastructure, the following most energy-critical municipal infrastructures were selected, which present the highest annual energy consumption:

1. Town Hall of the Municipality of Trikala
2. Cultural Center of the Municipality of Trikala
3. Indoor Swimming Pool, Municipal Sports Facilities of Barra
4. Municipal Depot
5. Outdoor Swimming Pool, Ag. Georgiou
6. Municipal Technical Service - Social Welfare building

For the sake of scalability, the equipment needed for the system operation was also categorized into four respective levels of varying degrees of complexity and power consumption/control capabilities.

- **Subsystem for Level A infrastructure** *(145 installations)*
  - *Central Power Supply Meter (Three-Phase or Single Phase)* for the measurement of voltage, voltage, energy and power
  - *Thermostat* for measurement of temperature, humidity and brightness and room temperature control
- **Subsystem for Level B infrastructure** *(24 installations)*
  - Level A Equipment
  - *Lighting Line Controller* for the on/off control of a selected lighting line
  - *Air Conditioner Controller via IR* for on/off control and customization of air conditioning units
  - *Liquid Tank Level Gauge* for the measurement of diesel reserves
- **Subsystem for Level C infrastructure** *(6 installations)*
  - Level B Equipment
  - *Power Line Meter* for the measurement of voltage, voltage, energy and power
- **Subsystem for Level D infrastructure** *(6 installations)*
  - *Level C Equipment*
  - *Customized controls and full measurement* of all special energy parameters.

The system's software was specified to meet the needs of remote monitoring, controlling, analyzing and managing energy consumption in the selected infrastructures of the Municipality of Trikala. Besides the support of all the devices described in the project and with the support of the natural gas distribution management company enaon EDA, it is planned to monitor the natural gas consumption in the municipal infrastructures that use this energy source for heating via the readings provided by their remote metering solution.

Table 1. Analysis of selected municipal infrastructure according to their location, area and use and their inclusion to the system coverage

Level Legend:
Level A
Level B
Level C

Categories of infrastructure	Central Sector (urban & sub-urban)					Sector A (rural)					Sector B (rural)					Overall included/total
	<100m²	>=100m², <500m²	>=500m², <1,000m²	>=1,000m², <2,000m²	>=2,000m²	<100m²	>=100m², <500m²	>=500m², <1,000m²	>=1,000m², <2,000m²	>=2,000m²	<100m²	>=100m², <500m²	>=500m², <1,000m²	>=1,000m², <2,000m²	>=2,000m²	
Sports Facility		1		1	1											**2/3**
Multi-purpose hall		1					1				1	1				**0/4**
Other	1	1														**0/2**
Municipal infrastructure	2	1	2													**3/5**
Clinic		1														**0/1**
Elderly support center		6	1	1		1	1				2	1				**13/13**
Cultural center	1	5	1	2	2											**11/11**
Community store						7	5	2			1	6	1			**0/22**
Office building	4	6		1												**7/11**
Kindergarten	1	10	2				2	1				3				**19/19**
School	6	29	14	8	12	7	12	1	2			18	4		1	**114/114**
School (energy-critical)			1	2	3											**6/6**
Underground parking	1				1											**0/2**
Overall included/total	**8/16**	**58/61**	**21/21**	**15/15**	**17/19**	**8/15**	**15/21**	**2/4**	**2/2**	**0/0**	**2/4**	**22/29**	**4/5**	**0/0**	**1/1**	**175/213**

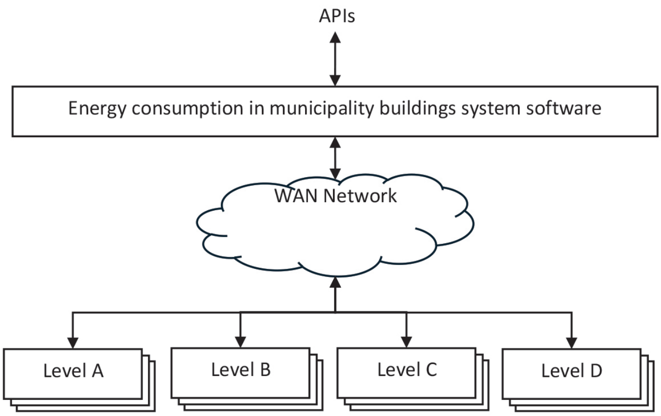

Figure 9. Energy consumption in municipal buildings system architecture

From the above, it is evident that the energy monitoring system in municipal buildings proposed in "RESTART mAI City" project, provides the necessary technical infrastructure for modeling and controlling the most important energy consumptions. Despite the fact that it will currently lack the capability of exhaustive drilling down of the full set of parameters affecting buildings consumption, it was designed with scope and field extension flexibility in mind. Thus, while the degree of maturity of the system under development can support the development of an analytical digital twin to a limited extent, the system architecture allows for targeted scaling to the point where it proves to be feasible and economically viable for its purpose.

Smart irrigation

The irrigation system of municipal green spaces is an integrated and automated smart irrigation system that aims at the efficient management of water resources in the green spaces of the Municipality of Trikala. The system includes automatic irrigation systems, weather stations and air quality measurement systems. It consists of electrovalves controlled via IoT nodes, enabling automated control of the water supply with the aim of reducing consumption, increasing efficiency and improving vegetation quality. At the same time, air quality sensors monitor PM2.5 and PM10 levels, are used to calculate the Air Quality Index (AQI), as described in [20] and [21].

The location of the equipment was selected to optimally meet the needs of irrigation and monitoring microclimatic conditions in the green spaces of the Municipality of Trikala. These areas are mostly supplied with water from the city's water supply network, whose pressure at the low ground level (excluding hills) of the city amounts to 2.5atm (159 spaces), while in special cases irrigation is done by pumping river water (5 spaces). As a rule, each space corresponds to a central water supply of 3/4" or 1" for small and 2" for larger corresponding areas. The central supply is divided into one or more individual drains of the irrigation system (stops), which are organized in one or more wells (see Table 2).

Table 2. Quantitive field analysis of selected municipal green spaces irrigation infrastructure, according the automation significance and the stops density per well.

		High significance		**Low significance**	
		Wells	*Stops*	*Wells*	*Stops*
Without well			2		5
Stops per well	*1*	221	221	41	41
	2	40	80	2	4
	3	17	51	-	-
	4	16	64	1	4
	8	2	16	-	-
Overall		**296**	**434**	**44**	**54**

Based on the above analysis and taking into consideration the project budget and the expected cost-benefit result, the following development guidelines for this system have been defined:

- **Subsystems for automatic irrigation with 1" electrovalves**, suitable for green spaces with small to medium irrigation needs *(104 installations):*
  - In areas with constant water pressure (~2.5 atm) covered by the central water supply network.
  - At points where rotational activation of the stops is required for optimal water consumption (limit 250lt/hr).
  - Location preferably in:
  - Playgrounds
    - Traffic Islands
    - Small parks and squares
    - Areas with ornamental shrubs and low vegetation
- **Subsystems for automatic irrigation with 1½" electrovalves**, suitable for green spaces with small to medium irrigation needs *(15 installations):*
  - In places where the water pressure is high and stable.
  - In central supply 2" with distribution in individual drains per well.
  - By organizing the stops in wells to avoid overconsumption and optimal water management.
  - Location preferably in:
    - Large parks and sports venues
    - Areas with heavy vegetation or trees
    - Points with high water supply requirements
- **Subsystems for meteorological measurement**, suitable for areas with differentiated microclimatic characteristics *(5 installations):*

- For rainfall recording and switching off electric valves in case of rain.
- For wind monitoring to avoid irrigation in adverse conditions.
- To collect temperature, humidity and solar radiation data for irrigation planning.
- Location preferably in:
  - High points of the city for more accurate weather recording.
  - Central nodes for collecting data at representative locations.
  - Parks with a large area for accurate monitoring of microclimatic conditions.

- **Subsystem for air quality measurement**, suitable for high-traffic and traffic-congested areas *(20 installations):*
  - For monitoring PM2.5 and PM10 levels.
  - For the calculation of the Air Quality Index (AQI).
  - For information to citizens through the Municipality's public website.
  - Location preferably in:
    - Squares and parks with a high concentration of citizens.
    - Close to road junctions and intersections with high traffic.
    - Close to weather stations for spatially correlated data collection.

Taking into account the above guidelines, the Department of Urban Green & Environment of the Municipality of Trikala, as the main responsible for the management and operation of the system, proceeded to the exact identification of the installation points of the subsystems. This choice ensured an optimal coupling between the needs of the physical field and the supporting technical system, covering a key prerequisite for the successful implementation of a digital twin.

The system support software was specified to provide full remote control and automation of irrigation in the green spaces of the Municipality of Trikala, with the application of multifactorial rules that take into account real-time data for the remote control of electric valves and irrigation systems. Also, by analyzing the data of the devices (electric valves, weather stations, air quality meters, etc.), to calculate the optimal time and the optimal amount of irrigation. In addition, calculate the Air Quality Index (AQI) for the individual measured environmental indicators (PM2.5 and PM10).

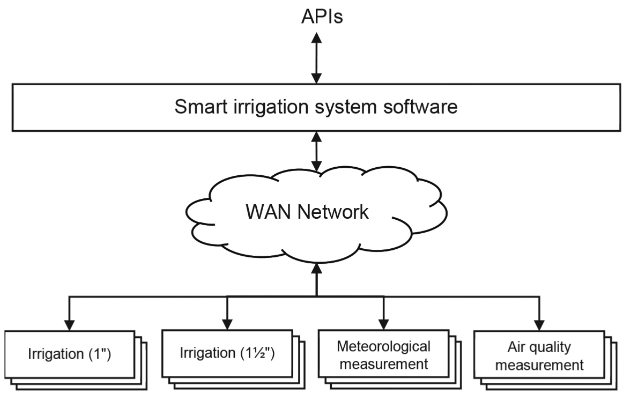

Figure 10. Smart irrigation system architecture

Moreover, the aforementioned subsystems' implementation is based on the use of similar IoT nodes, of very small size, which can be placed (IP67 protected) inside wells, manholes, pillars or even open spaces. Each node has the ability to record measurements from various sensors (e.g. humidity sensors, weather stations, air quality meters, etc.) as well as to control or automate processes through electrovalves or relays. This fact allows for easy configuration and expansion of the overall system according to specified needs, even up to the point of supporting a full digital twin for the irrigation of the green spaces of the Municipality of Trikala.

Smart city platform

In extension to the above vertical systems, which, as described, can easily evolve to thematical digital twins, the architecture introduced by the "RESTART mAI City" project can offer a broader twinning perspective. One of its basic structural principles is the consolidation of vertical systems data and control into three horizontal systems that consist of the smart city platform: a GIS platform and two distinct systems for data gathering and notification. While each of the latter ones is specialized either to machine-to-machine (M2M) or to machine-to-human (M2H) communication role, they can temporally support both roles in case of disaster mitigation situations [21].

This infrastructure essentially gathers conformed data from a virtually unlimited variety of sources and at the same time can perform fusion in processing and information presentation. In other words, the proposed technical system can support under suitable circumstances the creation of digital twin models of more complex and ever-changing physical systems that depend on diverse parameters such as a whole city. Architecture permits the creation of such a global digital twin, based on either the collaboration of lesser thematic digital twins or the global modeling and interpretation of thematic data as a whole. In any case, the infrastructure developed by "RESTART mAI City" project is planned to deploy digital twin techniques.

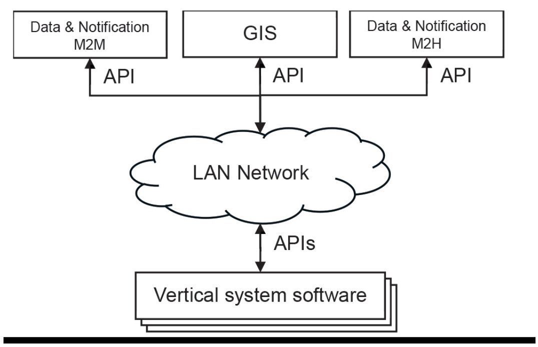

Figure 11. Interoperability structure of vertical systems and the smart city platform in the "RESTART mAI City" project architecture context.

CONCLUSIONS

Digital twin applications in smart cities have become extremely popular latest years thanks to the developments of technologies and tools such as Industry 4.0, Internet of Things, Sensors, Artificial Intelligence and Machine learning. As these technologies are new, not mature and demand a lot of investments and resources to be implemented, it is not very easy for most of the cities to adopt them, although the expected results and gains are significant in many sectors of everyday life for the cities, the residents and the city managers.

In the case of Trikala, considered in this chapter, digital twin applications are at varying stages of development. Certain of these applications need extensive infrastructure, which is still expensive and time-consuming to implement. However, technological advancements and standardization of processes are expected to make these projects more feasible in the coming years. To support these efforts, governments and the European Union should provide suitable financial and funding tools and should also define a framework allowing the management of legal issues to address, including concerns such as data privacy, the reliability of decision-making, and the safety and security of critical infrastructures.

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