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ORIGINAL ARTICLE

Digital twins for intelligent cities: the case study of Matera

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Abstract

The digital twin (DT) paradigm provides a purpose-built digital representation of a physical system. DTs are often composed by several interconnected models, which need to be specifically tailored to fit the DT purposes. The objective of this work is the development of an urban digital twin (UDT) for the city of Matera, following urban intelligence (UI) paradigm. The latter leverages the multi-disciplinary integration and optimization of the city systems and subsystems to develop purpose-driven DTs and support the decision-making process. The UDT is intended to support governance, stakeholders, and citizens, integrating morphological data for the city representation, reliable simulation tools and data-driven methods for the city state prediction (e.g., traffic, solar irradiation), optimization algorithms for planning and emergency response, sensors for vehicle and pedestrian traffic volumes and environmental monitoring (e.g., pollutant distributions), and a participatory data collection process from the citizens. A Data Lake is used to make available to the UDT modules the data produced by the morphological representation, simulations/data-driven methods, sensors, and the participatory data. The Data Lake provides a standardized approach for the aggregation and extraction of information. Finally, an Urban Sensing Engine supports the decision-making process with artificial intelligence forms of reasoning, to effectively combine the information produced by the UDT components.

Keywords Digital twin · Urban intelligence · Optimization · 3D semantic modelling

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1 Introduction

City development and management should address continuously evolving environmental, economic, and societal conditions. To face this challenge, multidisciplinary approaches are of interest. These allow to take into account and investigate the interaction among the different physical layers that constitute the city as well as their interaction with the inhabitants [1]. To be effectively applied multidisciplinary approaches require the use of sensors, mathematical modeling, and big data to understand and, possibly, predict the layers dynamics, interactions, and evolution; the development of automatic reactions to rapidly evolving situations (such as emergency response); the increase of the interactivity and involvement of the inhabitants.

Following a consolidated trend in the scientific community [2–4], a further step can be performed combining the different multidisciplinary approaches within a single architecture called a Digital Twin. The final goal of such an approach is to provide a tool with a comprehensive modelling and representation of a complex and multi-scale system.

A Digital Twin (DT) is the digital model of a physical asset coupled together by connections of data and information [3], which enables a wide set of operations (such as optimization, control, management, and analysis) to be carried out fully in the digital realm. Initially conceived in the frame of manufacturing processes and 4.0 Industry, the DT concept was soon adopted by many other sectors, extended to include both living and non-living assets, and underwent substantial clarifications which allowed to fine-tune its key-features and potentialities. With respect to this framework, a consensus does not exist yet in the scientific community about the definition of the DT concept applied to the urban scale (Urban Digital Twin, UDT), being the landscape of its ongoing applications particularly wide [5].

Nevertheless, a survey on the short list of relevant definitions so far proposed [6–9] allows to highlight some recurrent features, characterizing the UDT as: (i) a virtual replica of a city including its assets, systems and processes, coupled with the city and thus evolving with it; (ii) a reliable simulation and learning environment based on different sources of data, mathematical models, and artificial intelligence (AI) tools.

These features enable the definition of some recurrent goals for an UDT, such as: (i) generating a deeper knowledge and better information on the city; (ii) developing consistent scenarios for the city's future; (iii) supporting urban management and decision-making in response to policy problems. The potential should also be stressed of UDT to raising citizens' awareness on sensitive urban issues, as well as of enhancing their participation in knowledge building and city planning processes, e.g., thanks to augmented/virtual reality (AR/VR) solutions or crowdsourcing tools [10–14].

A quick review on the above mentioned literature shows infrastructures, energy, noise, mobility, social behaviours, water, and disaster management as the leading urban topics addressed by current UDTs developments, while little space seems to be reserved to the research in the field of data and models integration.

With respect to this background, the Urban Intelligence (UI) approach proposed by the National Research Council of Italy (CNR) pursues the development of an enhanced UDT technology by:

1. exploring the potentiality of multi-disciplinary integration and optimization across the thematic layers of a city, with the aim of evolving the current planning, decision-making, and governance schemes in the direction of a higher transparency, objectivity, and adaptability as well as of a stronger multi-actor collaboration [15];
2. implementing the enhanced UDT as a "socio-physical-cyber system" [6, 16, 17] aimed at integrating socio-economic dynamics and community behaviours among

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its thematic layers. In particular, this paper describes the first findings and results from the application of such an enhanced UDT model on the Italian city of Matera.

The paper is structured as follows: the next Sect. 2 describes the case study of the city of Matera, introducing the structure and the purposes of the Digital Twin of the city. Section 3 presents the architecture of the proposed UDT, describing in detail its subsystems, their functionalities and their implementation. In Sect. 4, the capabilities and the results of the proposed UDT platform are showed, assessing its usability in a real case scenario. Finally, Sect. 5 summarizes the paper and draws out the final conclusions.

2 The case study of Matera

Matera is a city in the region of Basilicata, in Southern Italy, characterised by a complex morphology with bare highland plateaus and deep ravines. The terrain consists mainly of calcarenite, a sedimentary rock, soft and easily modelled. This has allowed the formation of numerous caves, facilitated the procurement of building material, and enabled the excavation of canals and cisterns. The heart of the historical centre is *Piazza Vittorio Veneto* and the ancient Hypogeum located underneath. The latter consists of numerous underground levels and contains a huge water reservoir, the *Palombaro lungo*. The adjacent "Sassi district" is a complex of cave dwellings carved into the ancient river canyon. By the late 1800 s, the site became noted for intractable poverty and poor sanitation. Renewed vision and investment led to the cave dwellings becoming a noted historic tourism destination, a vibrant arts community, and a UNESCO world heritage site since 1993. After being European Capital of Culture in 2019, Matera was selected as an innovation hub, to host the "House of Emerging Technologies" funded by the Italian Ministry of Economic Development, including the realisation of the UDT of the city.

2.1 The structure of the digital twin for Matera

The development of the Matera's UDT is grounded into a set of Primary Thematic Objectives (PTO) which were co-defined by CNR together with the Municipality of Matera, with special regard to:

(i) monitoring the touristic fluxes in the city (especially pedestrian);
(ii) monitoring the status of the urban environment;
(iii) improving the environmental comfort of the urban open spaces;
(iv) facilitating the access of citizens to city's primary services;
(v) enhancing the accessibility for disadvantaged social groups.

In particular, the enhanced UDT (which is now in its beta-development phase) is focused on an urban area roughly including the historical centre and its first outskirts. Based on these PTOs, a set of main actor profiles are defined entitled of the UDT usage, and for each of them the related frames of access, the modes of utilization, the specific use cases, and the benefits expected are also highlighted. These profiles are:

1. "Governance": who is entrusted with the final decision-making on the city's future scenarios (e.g., Public Administrators);
2. "Policy Making": who is involved in key knowledge-building and scenarios-making processes (e.g., technicians, enterprises, associations and citizens);
3. "End-users": the citizens and the community in general as city's end-users.

This taxonomy embeds the main goal of the UI approach that is to support the multi-level and multi-actor collaboration in the urban management process. Furthermore, the UI approach allows to separately develop the digital tools, the methodologies, and the algorithms guaranteeing their seamless integration within the UDT of the city.

3 Building the urban digital twin of Matera

3.1 System architecture overview

The overview of the system architecture adopted for the implementation of the proposed UDT of the city of Matera is depicted in Fig. 1. The architecture is composed of three main parts. The first part, shown in the left side of Fig. 1, includes hardware/software components devoted to provide a *Digitization of the City*, creating its digital counterpart by collecting and processing morphological data of buildings and terrains, the environmental and traffic data from sensors installed in crucial points of the city and, finally, getting participatory data from citizens and tourists through online geolocated questionnaires (as described in detail in next Sects. 3.2.1, 3.2.2, and 3.2.3). These data are transmitted to the cloud and gathered by the *Data Lake* component of the architecture (Sect. 3.3), shown in the centre part of the figure, which stores, integrates and enriches them with additional metadata to facilitate query and retrieval operations, and also provides a common REST API interface to ease communications and data sharing among the modules of the architecture. Finally, there are a number of subsystems included in the *Processing Modules* part of the architecture, depicted on the right side of Fig. 1. These subsystems pro-

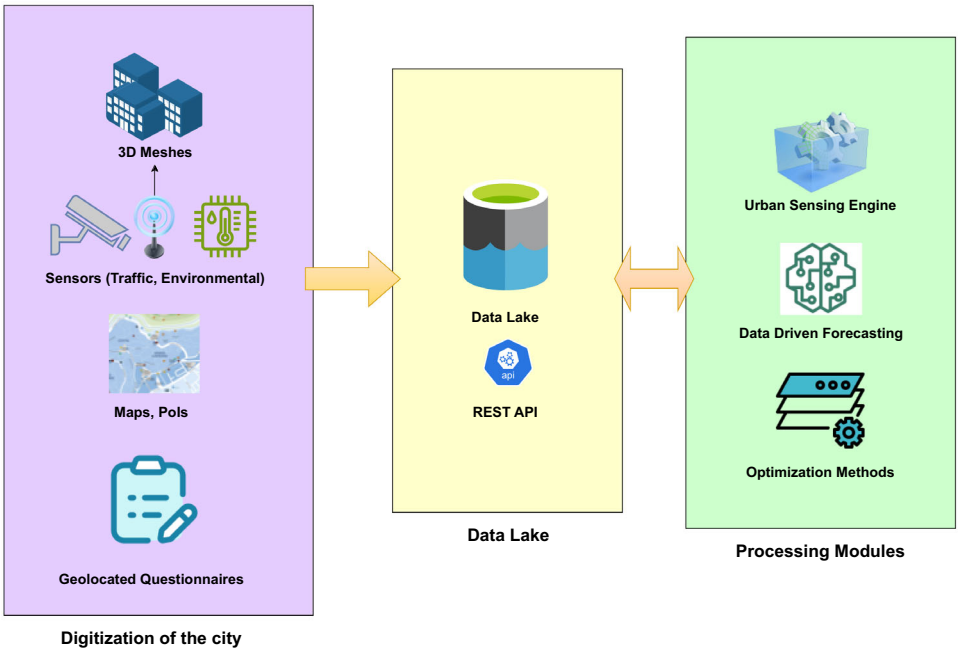

Fig. 1 System architecture of the proposed urban digital twin

cess the available data to produce the expected information. This is then used to support the development of the governance and policy making strategies to enhance the quality of the services of the city and the wellbeing of the community. These modules are, namely: i) Urban Sensing Engine (Sect. 3.4), which aims at providing a support to the intervention policies of the policy makers by mixing deliberative and reactive forms of reasoning approaches; ii) Optimization mathematical models (Sect. 3.5) considering personalized objective functions and constraints, and taking into account both the geographical structure of the city and the information coming from sensors and forecast/simulation services; iii) Data driven forecasting modules (Sect. 3.6), which predict the occupancy of the Points of Interest (PoIs) of the city. The details of each part of the system architecture are described in the following Sections.

3.2 Making the city intelligent

The UDT relies on data layers, each one representing the digital counterpart of a specific aspect of the city and encoding the related knowledge, see Fig. 2 for a schematic representation of the UDT. One fundamental data layer is the aspect, extent, and morphology of the city itself, namely a geometric layer, which is designed as a 3D model of the city. The 3D model can be analysed to directly answer user queries such as "what is the slope of this route?", "is the playground still under the sun?", or provide morphological quantitative measures to more complex objectives that require integration with other layers (e.g., noise, traffic, and air pollution). Spatial information related to the different city systems are organized as a TIS (Territorial Information System), structured as a layered, GIS-based tool hosting a great variety of geo-referred data gathered from different sources (from urban plans to points of interest or participatory inputs, and the like). Such TIS is merged within the Data Lake by adopting a geojson format, which allows its interoperability with the other UDT services: the result is an "intelligent TIS", the contents of which are purposely shared across the whole ecosystem in order e.g. to characterize graph arcs, and in this way to provide further inputs to the UDT algorithms, or to be annotated on the 3D model.

3.2.1 Morphological data collection

To realize the geometric layer of the UDT, a digital 3D representation is reconstructed of the terrain and of the built environment, with their shape and features; these elements are characterized by a three-dimensional nature, i.e., having a spatial extension, but can also bear knowledge in relation to their meaning, functionality, or context of use. The addition of knowledge to a portion of geometry is here called semantic annotation. For instance, a street can be annotated with information about its slope or a building with its energy consumption index. Furthermore, digital representations enable the application of mathematical models and algorithms to perform analysis, simulation, and prediction that are useful in responding to societal demands and needs, such as environmental monitoring and risk assessment [18, 19].

The geometry of the city is reconstructed as a triangle mesh surface from the data provided by the geo-portal of the Basilicata region [20]. The available data are a Digital

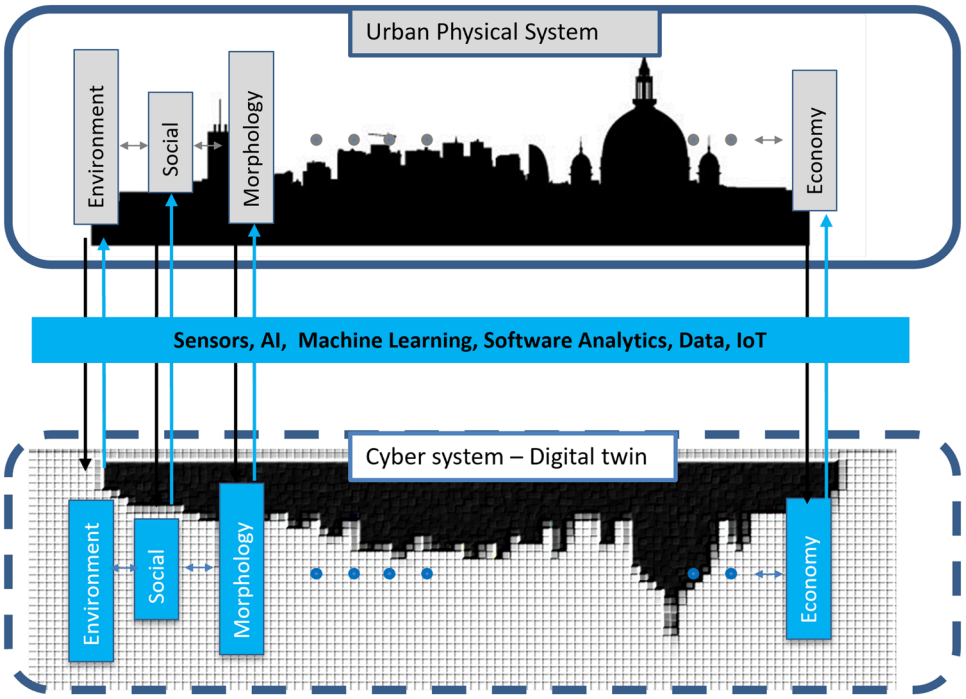

Fig. 2 Scheme of the UDT of a city

Surface Model (DSM) and a Digital Terrain Model (DTM), in the form of GeoTiff images with resolution corresponding to 5 m × 5 m (pixel width and height), elaborated from a LiDAR survey (see Fig. 3). Additional information and knowledge about the city is extracted from OpenStreetMap (OSM) [21].

In particular, buildings and streets are cross-referenced from OSM entities tagged as "building" or "highway" with the DTM and DSM to derive their real elevation as follows:

- resolve geometric and topological issues that may be present in building boundary polygons from OSM;
- insert building boundary polygons and street segments as constraints to generate a 2D triangulation of the ground around the buildings. Shewchuk's Triangle library is used to generate the constrained triangulation [22];
- assign to each point in the triangulation an elevation corresponding to that of the DTM cell in which the point is contained;
- assign each building a height equal to the average difference between corresponding DSM and DTM points within its boundary polygon and extrude the building base accordingly;
- close the extruded boundary by triangulating the corresponding polygon (again, using Triangle).

This approach allows generating approximations of the buildings at the LOD1 of the CityGML standard [23], with buildings as basic shapes without roof and façade details (see Fig. 4).

Once the geometry of the area has been generated, the model is semantically annotated following the approach described in [24]. By labelling street edges and building triangles with the corresponding OSM indexes, a biunivocal association between portions of the geometry and specific OSM entities and their attributes is created. Such an information can later be interrogated and analysed in relation to their geometric component, e.g., for selective visualization (see Fig. 5). More details about the reconstruction and annotation method can be found in [25].

In addition to the 3D representation generated by the previously described approach, it is essential to emphasize that creating high-fidelity 3D models of urban landscapes necessitates the utilization of suitable technologies capable of capturing extensive areas with geometric and visual details. Typically, a combination of various sensors and techniques is employed for surveying large and complex areas. In the implementation of the proposed UDT for the city of Matera, acquisition surveys were conducted through both aerial means and terrestrial laser scanners [26]. The resultant data were effectively employed by state-of-the-art 3D reconstruction methods to produce more detailed 3D models that represent specific areas within the city itself (an example is illustrated in Fig. 9).

Our reconstruction approach ensures the creation of an accurate and reliable 3D city model by integrating both open-licensed data, as recommended in [27], and several purpose-specific 3D data sources, including those generated ad hoc through various acquisition technologies and surveys. In our case study, the open data exhibited numer-

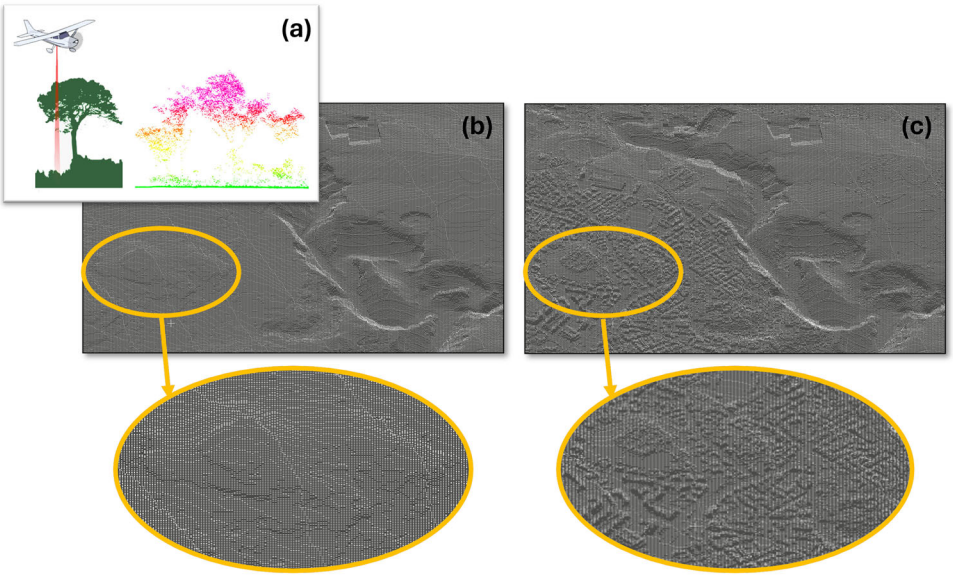

Fig. 3 **a** Airborne LiDAR data acquisition producing an annotated point cloud. **b** Digital surface model (DSM); **c** digital terrain model (DTM)

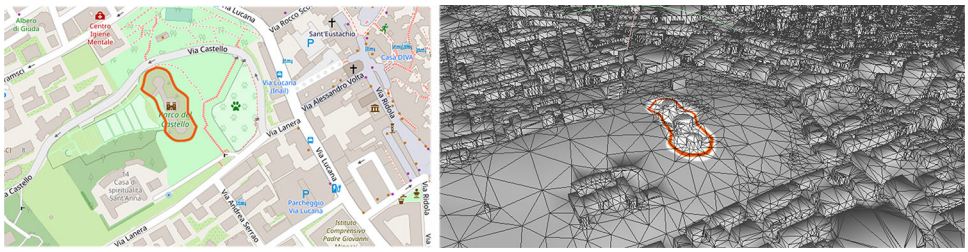

Fig. 4 From left to right: OSM map of the Matera city centre; the reconstructed geometric mesh model (the Tramontano Castle is highlighted for reference)

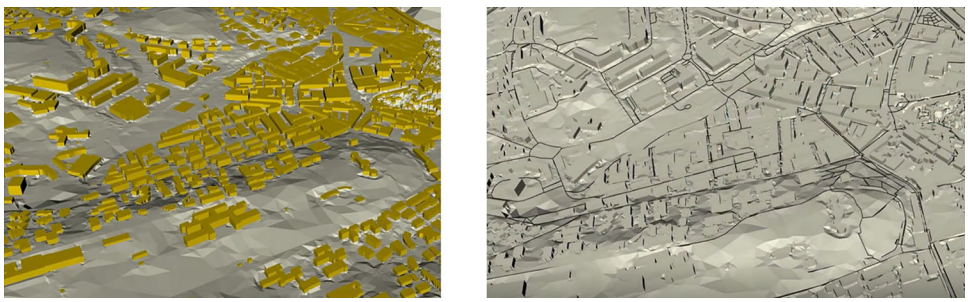

Fig. 5 Semantically annotated 3D model. From left to right: visualization of annotated elements: buildings and streets, respectively

ous geometric and topological inconsistencies, increasing the likelihood of reconstruction errors. To address this, the open data undergoes an initial pre-processing phase to remove these inconsistencies, thereby improving the overall reliability of the reconstruction. Also, data from acquisition surveys serves as a reference to detect and correct errors in the open data and incorporate additional reliable information. The resulting 3D city model enables precise and reliable measurements, as well as detailed morphological characterizations, as outlined in Sects. 4.1 and 4.2.

3.2.2 Real sensors and synthetic data collection

A network of sensors is implemented to collect real time data regarding to two main categories, namely: (i) the detection, counting, and monitoring of the accesses of vehicles and pedestrians and (ii) environmental monitoring. As to the detection, counting, and monitoring of the accesses of vehicles and pedestrians, the network monitors and counts vehicular transits at a number of road intersections and the number of pedestrian transits along specified pedestrian paths in the historical city center that are most accessed by tourists, the pedestrian accesses to outdoor places of social aggregation (such as parks/green areas) and the accesses to a number of sites typically visited by tourists (such as museums, churches, and historical sites). Vehicular monitoring is realized through cameras equipped with on-board ad hoc AI software able to recognize the transit of a vehicle, the direction of the transit (i.e., entrance or exit from the monitored road section), and the type of the vehicle (i.e., private

car or commercial vehicle). An analysis of the traffic data derived from a previous measurement campaign performed by the Municipality of Matera in combination with the analysis of the road layout (one-way vs. two-way, presence of roundabouts, etc.) and the identification of social/cultural PoIs (such as schools, bus/train stations, museums) were used to identify and select the most critical roads sections characterized by traffic congestion and by the highest traffic volume. Similarly, for pedestrian monitoring, the cameras were placed along the paths most accessed by tourists as identified through the analysis of historical data made available by the Office of Tourism. The sensors are cameras with AI functionalities able to recognize when a pedestrian walked across a road section or enter/exit a given place and update a digital counter. The data acquired by the cameras (for both vehicular and pedestrian monitoring) are transmitted to the cloud and the Data Lake to be accessed through a dedicated web-app by the other modules of the UDT. The data are then processed and analysed to identify which is the best route to reach a specific location based on the actual conditions in order to avoid traffic jams and pedestrian crowds.

To perform environmental monitoring, the network of sensors acquires several key parameters, including air quality through the measurement of the concentration of particulate matter (PM2.5 and PM10) and gases (CO, NO_2, NO), rain fall amount, temperature, humidity, atmospheric pressure, and solar radiation. The environmental sensor network is realized with 10 multi-sensor stations, each equipped with reduced size sensors, characterized by a reasonably good accuracy with respect to the UDT monitoring requirements. This results in multi-sensor stations of reduced size allowing to increase the granularity of the deployment and the covering of a higher number of areas than with traditional monitoring stations. An optimization algorithm was developed to identify the optimal sites of installation of the multi-sensor stations, considering:

- the urban context, including: the presence of areas with high vehicular traffic and inter-modal exchange, the presence of sensitive PoIs, the population density;
- the morphological context of the area being monitored, such as the configuration of the roads and pedestrian paths, the presence of street canyons or other elements that can create areas of stagnation of the air or open areas that may be more subject to levels high solar irradiation;
- the architectural/landscape constraints that could have an impact on the identification of the installation sites;
- the specificity and accuracy of the sensor technology to be used in order to identify the size of the spatial range within which each type of sensor provides accurate measurements.

Georeferenced data of the morphology of the area of interest in Matera were acquired and analysed to identify and classify the areas with higher monitoring priority based on the presence of conditions with high vehicular traffic, the presence of sensitive PoIs, the population density, and the presence of street canyons. The COPERT model (available free of charge at: https://www.emisia.com/utilities/copert/), a standard model used at European level and developed by the European Environment Agency (EEA), was applied to calculate the maps of pollutant distribution in the area of interest of the UDT. The COPERT model was fed with information about the characteristics and type of vehicles circulating in the area of interest, the average speed of the vehicles based on the type of road section (e.g., urban with free-flowing traffic, urban in a reduced-speed area, urban in the area with poorly flowing road intersections), and ambient temperature (from historical data of monitoring stations located in Matera and managed by ARPA Basilicata). The area of interest was then discretized in a number of sub-areas with similar level of pollutant, as derived from the maps calculated through COPERT. Finally, the identification of the optimal installation sites was obtained by taking into consideration the variables described above, that is the urban context, the morphological context, the level of pollutant, the architectural constraints, and the specificity/accuracy of the sensors. The monitoring stations are connected to the cloud and transmit the data in real-time to the Data Lake through a dedicated web-app.

To allow an early testing and development of the data-driven model for forecasting (see Sect. 3.6) synthetic data are used. Specifically, time histories of PoIs occupation are produced by means of superposition of elementary functions, such as trigonometric and Gaussian functions. These functions are characterized by different periods to reproduce hourly, daily, weekly, and monthly fluctuations of the PoIs occupations. Such fluctuations are modelled on the occupation trends of the PoIs as identified by historical data available to the authors.

3.2.3 Participatory data collection

Local communities are a fundamental source of data and info about how the people experience, understand and live their city. Such data can broaden the scope of the UDT by being integrated with other data sources (such as sensors or databases), with the aim of generating a more comprehensive and people-oriented understanding of the global behaviour of a city intended as a complex socio-physical system. For this reason, the PPGIS (Public Participatory GIS) webtool Maptionnaire[1] was adopted, which allows to carry out large scale surveys on a geo-referenced interface where to pinpoint community feedbacks by associating them to specific

[1] Developed by Mapita OI, https://maptionnaire.com/.

elements of the urban scene. In particular, the "Teen Maps Matera" (TMT) project, carried out in cooperation with the local high schools, reached out to the young population of the city (15-to-19-year-old) by engaging students in a wide-scale community mapping experience. A questionnaire was co-designed with the schools, in which information were asked on themes such as the most meaningful places where the youngsters could develop their interests and passions and they reach them, or the urban connections to be enhanced in order to improve their accessibility. More than 3.000 students (around 60% of the total high school students of the city) answered the questionnaire, and geo-referred as many places and connections. Gathered data represent an important database describing behaviours and habits of the young population of Matera, and represent the first set of a "Social Twin" of the city. Furthermore, such data were post-processed into layers for the intelligent TIS, allowing to overlay the community dataset with other layers (e.g., urban plans), or to carry out complex queries by cross-matching data and attributes from different layers, thus enabling direct comparisons (e.g., checking the current mobility scenarios with the needs expressed by people) or deeper correlation analyses. The results can be downloaded from Maptionnaire as ESRI shapefiles linked to an Excel database, to be post-processed in a GIS environment. Figure 6 shows some preliminary results from the survey. In detail, in the first image on the top left we visualize the concentration of all the places mapped by the boys; on the top right we visualize the mapping of recreational activities; on the bottom left we visualize sports activities; and on the bottom right the connections between neighbourhoods that the boys would like to strengthen.

3.3 Data lake

The Data Lake has the main purpose of collecting the data related to the digitization of the city (georeferenced maps, 3D meshes, sensors' data, filled questionnaires, etc.), as well as any other useful information for the UDT system, such as irradiation data or binary files. Furthermore, it can store the results of the processing of the information, obtained as output from Urban Sensing Engine (Sect. 3.4), the optimization modules (Sect. 3.5), and the forecasting models (Sect. 3.6), as well as to share such information among the different components of the UDT. The Data Lake supports the integration of the heterogeneous data acquired, enriching them with additional metadata for querying and retrieving operations. In this way, the Data Lake also acts as an integration infrastructure, facilitating the inter-communications and the exchange of information among the modules of the UDT (as described more in detail in [28, 29]). Finally, it also offers basic Extract, Transform and Load (ETL) functionalities for the aggregation of data and the extraction of information.

The Data Lake is implemented using MongoDB NoSQL database, which offers the required performance level and is easily scalable. The schema-free feature of the NoSQL approach adopted by MongoDB allows to easily integrate any new data models, if required during the usage of the UDT system by the community. It also integrates the GridFS distributed file system, for the storage of large binary files, directly indexing them in the database. Finally, it exploits a SparkSQL MongoDB connector to efficiently execute ETL pipelines, following the approach described in [30].

The communication with the Data Lake is based on a REST API interface developed in Python, which offers a standard and unified interface to any module of the UDT, and supports and facilitates the integration of the subsystem of the proposed architecture [29]. The authentication and authorization services are managed by Keycloack [31], an open-source identity and access management framework, able to provide user federation, strong authentication, user management, and fine-grained authorization. Finally, a relevant service of the system lies on the Message Queue Telemetry Transport (MQTT) broker server, which can notify any module of the UDT (and also external components, such as user apps, websites and others) about the updates of specific information stored in the Data Lake, using a publish-subscribe mechanism. This approach permits the application consumers to immediately receive the information they are interested in processing as soon as it is produced. Figure 7 summarizes the submodules of the Data Lake, their functionalities, and the frameworks used to implement them.

The Data Lake has also the purpose of improving the reliability of the data. In a smart city environment, not all data can be always reliable, due to different causes, such as transmission errors, low battery or failures of the IoT devices, cyber attacks, and others [32]. Unreliable data could lead to wrong models and fake alerts by the UI. Therefore, data reliability assessment is very important in Smart City environments. On the other hand, this task could be challenging, due to the size and rate of the data, as well as to processing time constraints [33]. In the proposed architecture, the Data Lake includes specific functionalities to improve the reliability of data, implemented using the SparkSQL engine to ensure the required performance level.

In detail, a software agent monitors the status of the batteries (when available) of the IoT sensors that do not have a direct power connection, providing an alert to prevent data loss caused by low battery power. The same agent also monitors the deadline and the size of data consumption of the 4 G subscriptions, in the case of sensors connected through this technology. In this way, missing or wrong sensor data due to low batteries, or lack of 4 G connectivity are monitored and prevented.

Moreover, unreliable data in smart cities can be caused by network errors, malicious attacks, or failures in the edge

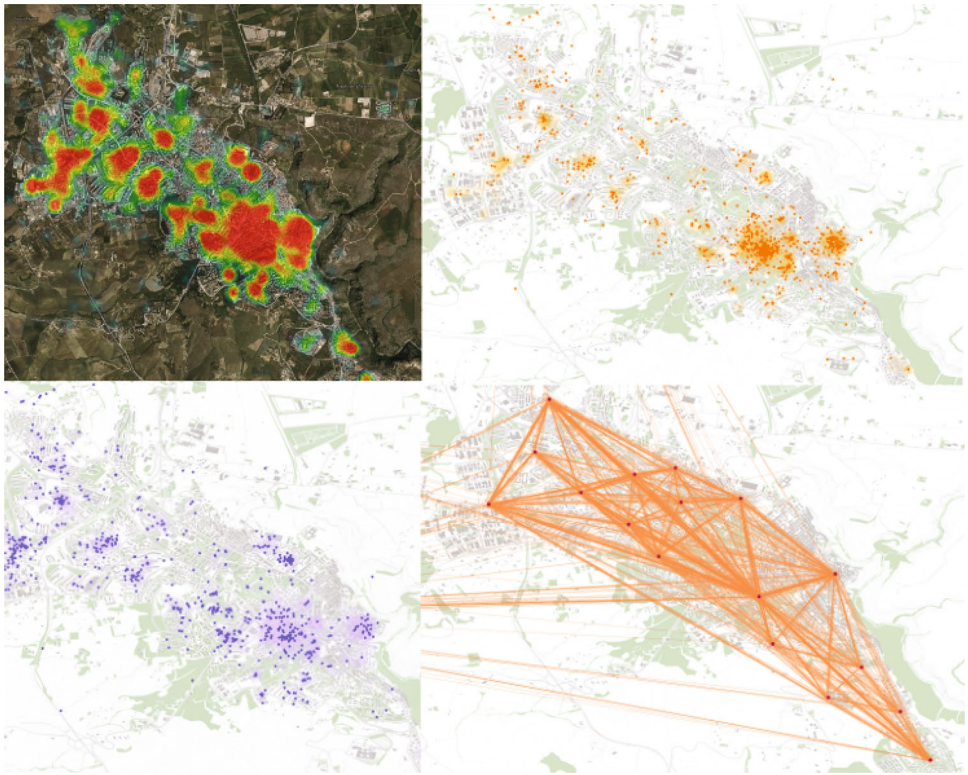

Fig. 6 Preliminary results from the TMT project; from left to right: heat map of all the mapped places (processed through the built-in visualizer of Maptionnaire); breakdown analysis (post-processed on QGIS), representing respectively the places mapped for leisure and sport activities, and the connections to be enhanced among the city neighbourhoods

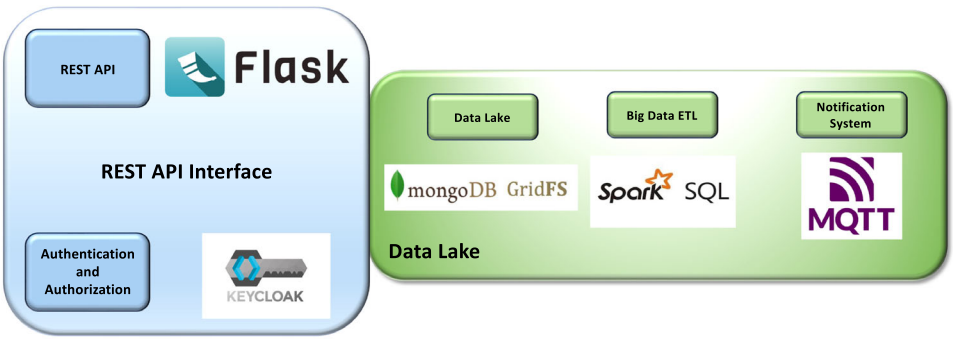

Fig. 7 Submodules of the Data Lake and corresponding implementation tools

systems of the IoT sensors [32]. Therefore, the proposed architecture includes additional mechanisms to minimize such kinds of data errors. Firstly, when the IoT data has a predefined and known periodic or spatial sampling time/area, the Data Lake continuously verifies the availability of all expected samples in their corresponding MongoDB collections. The data acquired by the sensors is also locally stored in the edge systems for at least one month from its acquisition (if the edge system has sufficient storage space, data is locally retained for more time). When a sample is missing in the Data Lake, it is automatically searched on the storage of the edge systems, and, if that data is available, it is immediately gathered by the Data Lake. This temporary unavailability of one or more samples, as well as the availability of the previously missing data in the Data Lake, are also notified to the other submodules of the UI, allowing them to eventually rerun their analyses as soon as the datasets have been corrected.

In addition, the Data Lake also periodically searches for two types of unexpected data values, namely *out of range* and *not frequent values*. In the first case, when the value range of the data acquired from a sensor is known, it is also stored in the Data Lake, allowing it to verify that the ranges of stored data are correct. If an out of range data is found, the same data (using its timestamp) is checked in the corresponding IoT edge system storage, following the same approach of the previous case. If a data with a correct range value is available on the edge, it is then retransmitted and stored in the Data Lake, and the event is notified to the UI submodules. On the other hand, if the out of range data is also stored on the edge, the maintenance service is contacted, asking to verify if there are hardware and/or network failures in the sensor

subsystem; also notifying the UI modules of the presence of an out of range data.

System errors or failures of the IoT sensors and malicious attacks could also produce not frequent data, which can lead to unreliable data sets. For example, due to one of the aforementioned events, a traffic sensor could transmit several 0 values (corresponding to no vehicles' passages) to the Data Lake, while during previous acquisitions in the same time and day of the week in the past months, the same sensor detected a huge vehicular traffic. This suspected behaviour is also monitored by our architecture. In detail, to minimize such kinds of errors, the Data Lake compares the samples corresponding to the same day of the week and the same time frame, and calculates their average and standard deviation. If the stored data is three times greater than the standard deviation value, the data is checked on the edge storage, and, if different data is available, they are acquired, alerting the submodules of the UI of the availability of corrected data. Otherwise, the maintenance service is alerted, asking to verify possible hardware and network issues in the sensor.

Finally, the data stored in the Data Lake can be accessed exclusively through the REST API, whose security is ensured by the adoption of the OAUTH 2.0 protocol for the authentication, and the HTTPS protocol and a VLAN for the communication.

3.4 The urban sensing engine

The Urban Sensing Engine aims at providing a set of "stratified" intervention policies that emerge from the interaction among different abstraction layers. In particular, to be effective in dynamic and unpredictable contexts, quite frequent in a city environment, the automated planning and optimization processes must be accompanied by the management of the uncertainty that may arise during the execution of the optimized solutions.

There are, in general, two complementary aspects that must be taken into account:

- *Insufficient and/or out of date data*. It is not always possible to have all the data necessary to build optimal solutions and keep them dynamically updated. Especially when dealing with real people, problems related to privacy can arise. Certain parameters, additionally, might be difficult to measure (e.g., psychological profiles, emotions, etc.). Consequently, even if the solutions generated turn out to be optimal according to the information hold by the system, they may not be optimal for real people.
- *Dynamism of the environment*. Although the information available to generate truly excellent solutions may be available, new information could emerge during their actualization on the territory. Therefore, a new solution could be to generated that takes into account the new information. However, this option has an intrinsic cost in terms of computation time that should be considered.

Taking inspiration from the dual-processing cognitive theories [34], the Urban Sensing Engine mixes *deliberative* and *reactive* forms of reasoning to support decision-makers in choosing their actions. In human beings, in particular, decision making involves high-level brain functions such as judgment and problem solving. These forms of reasoning, typical of humans, constitute what is often called deliberation or cognition. Rational and conscious processes, in addition, are integrated with more immediate processes, which occur automatically without real rational thinking, often referred to as intuition. In a similar way, the Urban Sensing Engine uses the optimized solutions generated by the system as "good guidelines to follow", reactively adapting them to the information that dynamically emerges from the city.

From a technical perspective, the deliberative services are implemented through forms of automated planning enhanced with semantic and numerical reasoning [35]. Specifically, the system exploits its internal knowledge, provided by experts through a formal language, to synthesize plans over time aimed at achieving particular objectives. The execution of such plans, however, must take reality into account. Instead of directly executing at proper time the planned actions, indeed, these are sent to a reactive component, which establishes what to do based on the information that dynamically emerges from the city. By relying on a rule-based system [36], this component is designed to solve complex problems by reasoning through bodies of knowledge represented mainly as if-then rules (called, in our case, policy-rules). The condition portion of each rule is tested against the current state of the working memory and, in case of positive result, the rule is fired and the consequent actions are executed. The execution of such actions can result in customized messages for particular users, as well as in a possible update of the system's data or "beliefs" or, even more, forecasts requests to data-driven models as well as solutions of combinatorial optimization problems, integrating the generated results as new beliefs and, consequently, once more reacting to them. It is worth noting that, just like in biological cognitive systems, the advantage comes from the joint use of the two approaches. The resulting system, in particular, can actively support the decision makers in a Cognition-driven Decision Support System style [37], dynamically *reacting* to changes perceived by the city sensors while long-term *planning* interventions for achieving desired urban goals. Suppose, as an example, that the Urban Sensing Engine perceives, through the data dynamically coming from the sensors, the deterioration of a road section. As a consequence of the application of a policy-rule, a road maintenance goal might be added to the

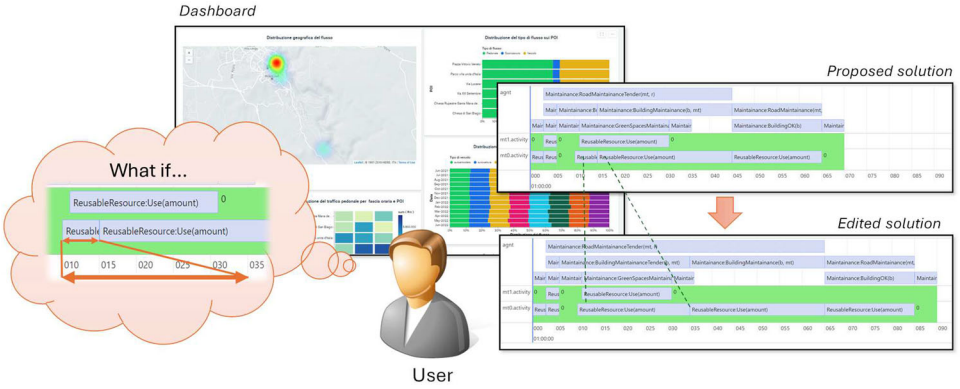

Fig. 8 The dashboard provides a comprehensive view of the current city state, and enables decision-makers to inspect automatically generated plans. These plans are shared across different users to support coordinated activity planning. Users can also edit the plans to perform "what-if" analysis

semantic-causal reasoner which, in response, would generate a causal sequence of activities compatible with the previously planned ones (e.g., already planned tenders, any large city celebrations, planned municipal employees vacations, etc.). The execution of such activities could start, for example, with the identification of a municipal technician, responsible for the road maintenance, who is assigned the task of preparing the documents for a tender for the maintenance of the deteriorated road section. From the plan executor, the activity is sent to the Urban Sensing Engine which reacts by producing a contextualized message for the designated technician, following him/her, in a similar way, along the entire procedure that leads to the repair of the damaged road section. Finally, it is worth noting that, as sketched in Fig. 8, the generated plans can be dynamically adapted from the feedback produced by the Urban Sensing Engine, as well as being consulted by decision-makers who, having additional information available, for example, from a city state analysis dashboard, might edit them to carry out "what-if" analysis, exploring scenarios such as an activity taking longer than expected, as shown in the figure.

3.5 Optimization methods and approaches

The optimization modules realized for the Matera UDT consists in mathematical optimization models designed with the aim of integrating information related to the geographical structure of the city (e.g., road network), with information on how the city is used by different actors (e.g., traffic or occupation), and by taking into account user preferences (e.g., desired destination, and accessibility profile) that are translated to specific objective functions and constraints. The developed mathematical models can be queried either by the users of the UDT, or by other stakeholders for simulation, scenario analysis, or other decision support purposes. In the following we detail 3 specific services: the orienteering, the personalized optimal path, and the optimal evacuation. The orienteering service allows to select and sequence a subset of PoIs based on the information of the map, together with user preferences. The service solves a specific instance of the orienteering problem. The orienteering [38] is a NP-Hard problem and several variants have been developed over time, for example to route visits during commercial events [39], or to design cruise tours [40]. The problem is defined on the road graph $G = (N, A)$ where $N = \{1, \ldots, n\}$ are the set of nodes and $A = N \times N$ is the set of arcs. The nodes consider n PoIs, being the starting point of the itinerary 1, and the target to be reached at the end of the tour n. The general objective of the orienteering is to find a path between a subset of PoIs which maximizes the sum of score associated to each PoI, while a maximum travelling time T_{max} is respected. The problem consider the following variables:

- $y_i \in \{0, 1\}$ equal to 1 if node $i \in N$ is selected for the visiting list, 0 otherwise;
- $x_{ij} \in \{0, 1\}$ equal to 1 if arc $i, j \in A$ is travelled, 0 otherwise;
- $a_i \geq 0$ storing the arrival time at node $i \in N$.

Constraints are imposed to guarantee that: the path starts from node 1 and ends on node n; each node is visited at most once; total travel time is less or equal T_{max}; subtours are eliminated.

With respect to the original orienteering problem, several other characteristics are considered in the UDT. In particular, the user input consists of the wish list of PoIs, and characteristics of the desired tour, such as typology (e.g., religious, historical, etc.), time window for visiting PoIs, maximum number of visits, information on waiting and service time at PoIs. Moreover, the travelling time is computed by considering the user, who may prefer longer routes but with less slopes, or prefer shadowed roads during summer season. By using a specific user interface, the objective function can be tailored on the user. In the released prototype it is possible to balance the rating of the PoI with the length of the tour, and it is also possible to indicate in objective function the non willingness to visit PoI with high occupation levels. These parameters are designed to be bound to other services of the

UDT, such as the occupation monitoring and forecasting. Once the parameters are set, the service finalizes the mathematical model, choosing the selected objective function and adding the specific constraints based on the user request, which are finally passed to the solver. As an example an objective function coded as *maxrating_mintime* equals to the function $f_1 = \alpha \sum_{i \in N} p_i y_i - \beta \sum_{(i,j) \in A} t_{ij} x_{ij}$ which aims at balancing the maximum rating with minimum travelling time. In the equation, p_i is the rating of the PoIs that can be associated also to comfort measures, while t_{ij} is the travelling time computed as a shortest path from i to j by the optimal path service as later explained.

The customization of the typology of PoIs visited is realized by acting on the model constraints. This is done considering a set of typologies $\mathcal{H}$, and defining a typology $h \in \mathcal{H}$ as the set of PoI indices belonging to that typology. Constraints are added to define minimum (H_h^-) and maximum (H_h^+) PoIs for each typology $h \in \mathcal{H}$ required by the user in the tour. It is important to note how the service is designed to be used as a planning tool for users which may be municipalities and decision makers who want to understand the potential impact of routes.

The personalized optimization path service realizes a fast shortest path service used with different purposes. The implementation allows to maintain in memory the road graph of the city. The graph is represented in standard notation, and updated with parameters related to different features, such as arc length, travelling time, slope, number of commercial shops along arcs. While some of these features are static (e.g., length of a road), other must be connected to live data (e.g., traffic). The minimum cost path from a source i to a node j with a specific cost function *attrib* is computed by the function *get_or_update_spath_dict(G, spath_dict, i, j, attr)*. A proactive preprocessing mechanism is designed to store the results of already computed shortest paths and track with a flag the paths that should be updated if some feature changes (e.g., the travelling time), based on sensor data or forecasted data. This mechanism allows the orienteering service to largely rely on pre-computed shortest paths when creating the origin–destination matrix, making the solution more efficient.

The optimized evacuation paths service provides optimized paths for evacuating, in the shortest amount of time, the visitors of an indoor exposition site (e.g., a museum). Problems regarding the definition of optimized evacuation paths have been extensively studied in the literature, from the seminal work in [41] up to the more recent contributions presented in [42–45]. Also, optimization and simulation mixed techniques have been considered in [46]. Here we used a new over time flow model implemented and solved as an Integer Linear problem. Because the model is only described in a yet unpublished working paper, we sketch here the detailed features. We associate the museum with an oriented graph $G = (N, A)$. The nodes N represent the physical places occupied by the visitors during the evacuation and can be partitioned into the sets $r_1, \ldots, r_h$ of rooms (corridors) of the museum. For each $u \in N$, let $r(u) \in R$ denote the room that contains node u and let c_u be the maximum number of visitors that can occupy node u at each instant of time. Let E be the set of rooms that represent the emergency exits of the museum, i.e. the places where the visitors should be located at the end of the evacuation process. Moreover, let U be the set of rooms that, usually due to the emergency that caused the evacuation, are not available for the evacuees to pass by. The arcs of the graph G model the possibility for the visitors to move from a node to the other. Each arc $a = (u, v) \in A$ is characterized by a travel time d_a (the time, in seconds, requested to go from node u to node v) and a capacity q_a (the maximum number of visitors that can use that arc at every second in time). In general, the arcs of A are symmetric, i.e., $(u, v) \in A$ implies $(v, u) \in A$. With two exceptions: i) it is not possible to leave from an exit room; that is, there are not arcs (u, v) with $r_u \in E$; ii) it is not possible to enter an area that is not available for the evacuation; this means that $(u, v) \notin A$, for each $u \notin U$ and $v \in U$.

The evacuation problem (EP) is then to find a set of paths in the graph G that lead each visitor to an exit room in the shortest amount of time, such problem is here modelled as a Linear Integer problem. The main variables used to define EP are indexed on the time horizon T of the evacuation. Such variables are:

- $x_{u,t}$ that is the number of visitors in node u at time t, for each $u \in N$ and each $t \in \{1, \ldots, T\}$;
- $y_{a,t}$ that is the number of visitors that enter arc a at time t, for each $a \in A$ and each $t \in \{1, \ldots, T\}$.

Then the proper linear constraints are defined to model: the flow conservation at the nodes of the graph over time; the arc capacities and travel times; the node capacities. The objective function minimizes the time in which the last visitor reaches an emergency exit.

When an emergency occurs, the evacuation service is called. The input of the call is defined by: i) the current distribution of the visitors within the rooms of the museum; ii) the indication of the unavailable rooms. Then the service applies a breadth search algorithm on the graph G in order to identify the visitors that cannot possibly reach any emergency exit. This is a crucial information for the museum management that, in case, can alert and activate a safety task force in order to rescue the blocked visitors. The tool can be used both with real presence data but also as simulation tool used to test emergence policies also in relation to internal displacement of expositions. Then, the EP model is solved either by the callable library of the commercial Integer Linear Programs solver *Gurobi* or by the open source solver *HiGHS via python*

PuLP. and the obtained optimal evacuation paths are returned as output of the service.

Reliability is an issue addressed during the design and the development / test phases of the optimization services. In particular, the orienteering and the shortest path services use the graph of the city road network extracted by OpenStreetMap. The repository is rich and detailed, but its open nature does not allow to assure high reliability levels. Thus, a cleaning phase was added in order to assure the validity of the network. The cleaned graph is stored in the Data Lake and in this way it is possible to benefit from all of the services offered by the Data Lake for update and conservation of the data. The optimal escape service is based on a graph representing the planimetry of a specific point of interest. At this aim the data were sourced by official institutions demanded to provide the official site planimetry that has been carefully checked, discretized and stored in the Data Lake. The reliability of the output is mainly the consistency of the paths. In particular, a relation among the path length and the other path attributes is maintained in order to avoid wrong or unrealistic and unreliable paths. For example, if a path in which the visit of commercial streets is requested, the algorithm provides a result in which the distance covered is at maximum twice the shortest path in length. This parameter can be checked during the tuning phase and it guarantees the consistency and reliability of the output.

3.6 Forecasting the city dynamics via data-driven methods

In order to allow the prediction of the occupancy of the PoIs, data-driven methods are used. These methods rely only on available data, such as, in this case, historical data of occupancy. In this work, the Dynamic Mode Decomposition (DMD) is used to provide the forecasting of the PoIs occupancy. The DMD formulation and nomenclature is taken from [47]. Specifically, consider a dynamical system described as

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathbf{f}(\mathbf{x}, t; \mu), \tag{1}$$

where $\mathbf{x}(t) \in \mathbb{R}^n$ represents the system's state at time t, μ contains the parameters of the system, and $\mathbf{f}(\cdot)$ represents its dynamics. The state $\mathbf{x}$ is generally large, with $n \gg 1$ and can represents, for instance, the discretization of partial differential equations at a number of discrete spatial points, or multi-channel/multi-variable time series.

Considering $\mathbf{f}(\mathbf{x}, t; \mu)$ as unknown, the DMD works with an equation-free perspective. Thus, only the system measurements are used to approximate the system dynamics and forecast the future states. Equation 1 is approximated by the DMD as a locally linear dynamical system defined as

$$\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t} = \mathcal{A}\mathbf{x} \tag{2}$$

with solution $\mathbf{x}(t) = \sum_{k=1}^{n} \phi_k \, b_k \, \exp(\omega_k t)$ where ϕ_k and ω_k are, respectively, the eigenvectors and the eigenvalues of the matrix $\mathcal{A}$ and the coefficients b_k are the coordinates of the initial condition $\mathbf{x}_0$ in the eigenvector basis, i.e. $\mathbf{b} = \Phi^{-1}\mathbf{x}_0$.

In general, the DMD can be viewed as a method to compute the eigenvalues and eigenvectors (modes) of a finite-dimensional linear model that approximates the infinite-dimensional linear Koopman operator [47], also known as the composition operator. Here, the DMD is applied to inherently finite-dimensional data and augmented (ADMD) with time derivatives of the data and time-shifted copies [48].

The reliability of the occupancy prediction service can be improved as historical data are made available, by comparing the prediction with the actual data. Such an approach can be used to continuously tune the ADMD parameters, such as the number of time derivatives and time-shifted copies. The continuous tune will make the service and its predictions reliable to changes in the city dynamic both for now-casting and forecasting.

4 Numerical results

4.1 Illumination/shading analysis

The geometric layer allows a detailed calculation of the shaded/illuminated areas at a given time and date, by analysing the built structures that can shadow ground points.

The algorithm is based on the intersections of rays of known inclination with the 3D city model. The ray's inclination depends on the Sun position in the sky, computed through the SOLPOS library [49] on the basis of the input parameters date and time.

For each vertex of the mesh representing the city, the implemented algorithm computes the ray to that vertex with the correct inclination and checks for intersections with the 3D model: if there are no intersections, then the vertex is illuminated; otherwise, the vertex is shaded.

An example of the shading calculation is shown in Fig. 9. This service can be used both for monitoring the current shading and for visualizing past or future situations. The computation time depends on the complexity of the 3D model, i.e., the number of vertices to be characterized and the number of surfaces to check for potential intersections. The output is a shadow map, actually a bit vector storing at the i-th position 1 if the i-th vertex is illuminated, 0 otherwise. At the current state, the output is limited to potential illumination/shading

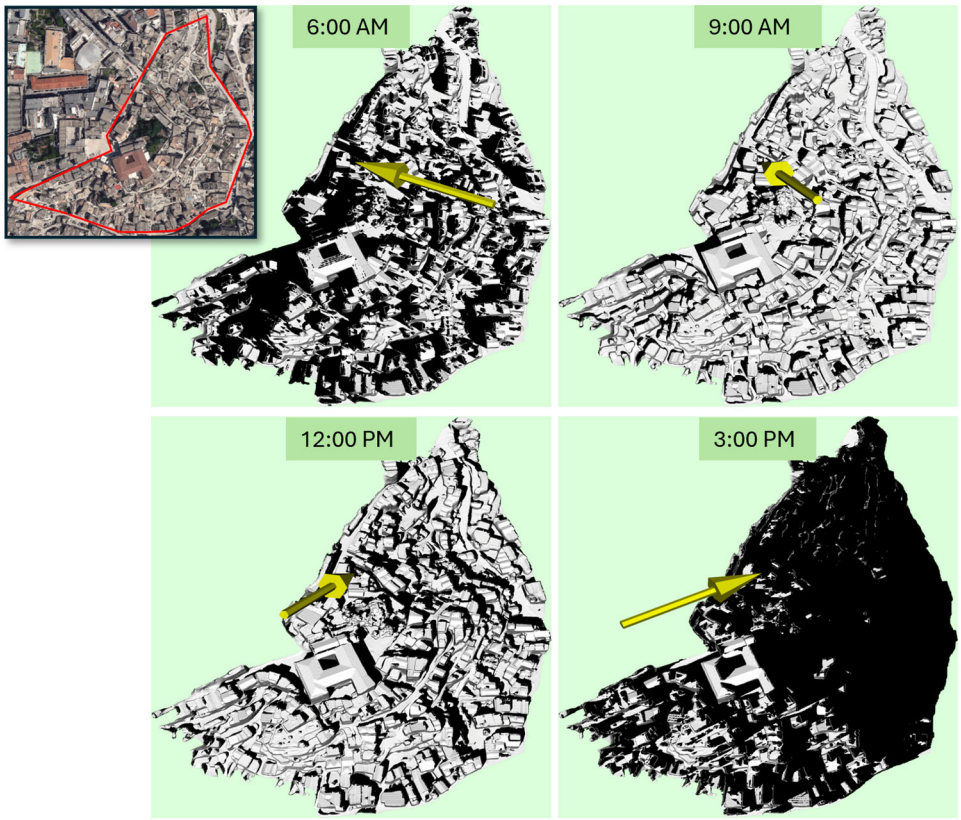

Fig. 9 Solar illumination expected on January 1st at different time (6:00 a.m., 9:00 a.m., 12:00 p.m., 3:00 p.m.) in a specific area of the city highlighted on the top-left. The 3D model integrates high-resolution data coming from airborne laser scanning. The direction of the sun rays is shown by the yellow arrow

based on date and time: no real time information or weather forecasts on sky coverage are taken into account; similarly, the output is binary (0 = shadow, 1 = light) while it could be a real value in the range [0–1] if sky coverage from satellite data or forecasts are taken into account, and/or physical light behaviour is considered (e.g., reflection and diffusion). As with the morphological characterization service (see below), the quality of the shading estimate depends on the resolution of the 3D model.

4.2 Morphological characterization

A morphological characterization service is designed to processes the geometric layer of the UDT, performing shape analysis on the 3D city model and annotating geometric elements with the extracted measures/dimensions. So far, the slope analysis of the road network has been implemented.

As anticipated in Sect. 3.2.1, the road network is represented in OSM as a graph, whose nodes are the branches of different routes and whose arcs are road sections connecting two nodes without branches. Each arc has been inserted as a set of edges in the 3D model and annotated consistently.

Given a road arc, whose slope is unknown, the algorithm proceeds as follows: mesh edges constituting the query road arc are identified; then, individual edge slope is calculated from the elevation of its incident vertices as the angle formed by the segment and the horizontal plane.

In general, road arcs are composed of a sequence of edges. The total slope of an arc is an aggregated value of the individual segment slopes. The service provides several alternatives, namely minimum, maximum, and average slope. As the road network is not frequently updated, this service will be launched only in case of changes to the network or to the 3D model (e.g., in case of a new survey campaign).

Beside annotating edges with their slope value, the results are saved in an output.json file storing the road graph with minimum, maximum, and average slope for every arc, shared among the UDT services through the Data Lake.

Figure 10 shows some results of the slope characterization of the road networks, using local, per segment values, or the average value on arcs. Future developments of this service may include the analysis of the width of streets, the slope and width of roofs, the detection and quantitative analysis of structures such as pavements, ramps, stairs, the identification of rough paths, etc.

4.3 Optimization results

All the optimization services are developed in Python and deployed as REST services. Such REST services are deployed on a virtual machine with 4 cores and 32 GB RAM.

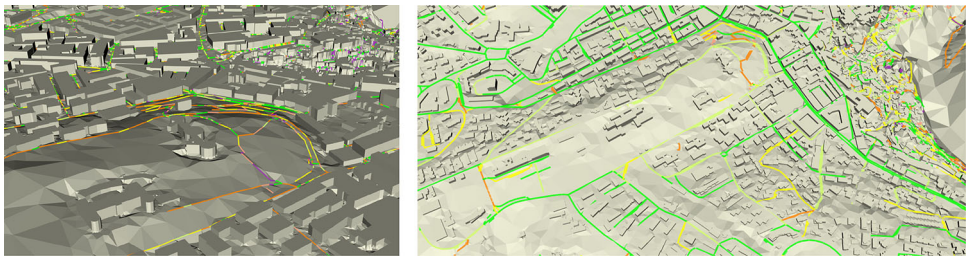

Fig. 10 Left: the road network is depicted according to local, per segment slope (from green = null slope to red = maximum slope—30° in this implementation; values above this threshold are visualized in violet for suggesting unrealistic values). Right: The road network is depicted according to the average slope (from green = null slope to red = 30°). Here the representation is smoother since an arc (between two branches) has an aggregated slope value

For the orienteering service, the tests are done over some PoIs of Matera. In particular 25 PoIs of different typologies (such as museum, square, church) are taken by OMS, where 20 different typologies exist. The tests are performed on a personal computer equipped with 8GB RAM and on the REST service machine. In both cases the running times for real instances are less than a second, ranging from 0.22 s for trips with 3 maximum stops to 0.66 with trips with 7 maximum stops allowed. In Fig. 11 is reported an example of solution of the orienteering when church-type PoIs are considered. We tested the orienteering service, with up to 100 PoIs and obtained the optimal solution in a maximum of 2.37 s. The base instance of 25 PoIs has been developed in order to consider a specific use case where the user, interacting through the user interface, filter the PoIs based on his preferences, and only after this filtering, the produced "wishlist" is given to the orienteering service for optimal orienteering. With respect to the personalized optimal paths service, the road graph originally downloaded by OSM and used to compute the shortest paths, cover the city of Matera, and contains 11,190 nodes and 12,086 arcs (with no processing of simple arcs). On this graph, the application of the Dijkstra algorithm to compute the shortest path required less than a second of computing on average. Figure 12 shows the result of the orienteering when different attributes are used to compute the shortest path. In particular, in the blue tour the slope is considered, while in the red tour the minimum length path is considered.

As for the optimized evacuation path service, the proposed algorithms are tested on a set of instances derived from the exposition site of the Hub San Rocco in Matera. In particular, the IV floor of the building is considered, which contains 23 rooms/corridors modelled by a graph with 66 nodes (see Fig. 13). Several tests are performed with dozens of visitors differently distributed in the rooms of the site, and with different combinations of unavailable rooms. In all cases, the identification of the isolated visitors is carried over in hundredths of a second, while the optimized evacuation paths are calculated at most in 5 s.

4.4 Occupation prediction

Figure 14 shows a detail of the synthetic occupancy history for the Belvedere Luigi Guerricchio (solid black line), along with the ADMD prediction (solid blue line) and the interval for which the prediction if performed (black dashed line). Please note that although DMD is not a machine learning (ML) method, the ML terminology is used here due to its widespread use and common understanding. The ADMD uses time derivatives up to the fourth order and time-shifted copies up to 2 days. Although the figure shows only 1 week of training, 28 days were used to train the ADMD. It is worth noting that the ADMD can accurately predict the occupancy bi-modal trend overall. Furthermore, the ADMD is accurate in predicting the time instant of the peak values with a small under/overestimation of the last peaks of the prediction.

5 Conclusions and future work

The development of an Urban Digital Twin (UDT) of the city of Matera was presented and its components discussed. The UDT aims at providing support to Governance, Stakeholders, and citizens in the development of the city and the decision-making process.

The UDT integrates morphological data for the city representation, simulation tools, and data-driven methods to predict the state of the city, optimization algorithms for path planning and emergency evacuation, sensors for vehicle and pedestrian traffic volumes and environmental monitoring, and data collection process from the citizens. The data collected from the modules and the sensors are collected and made available by a Data Lake. Finally, an Urban Sensing Engine is used to effectively combine the information produced by the UDT components.

Currently, the geometric layer and the related services of the UDT of Matera uses a LOD1 representation of the city landscape at a low resolution. This is sufficient to answer questions concerning the slope of paths in the modern part of

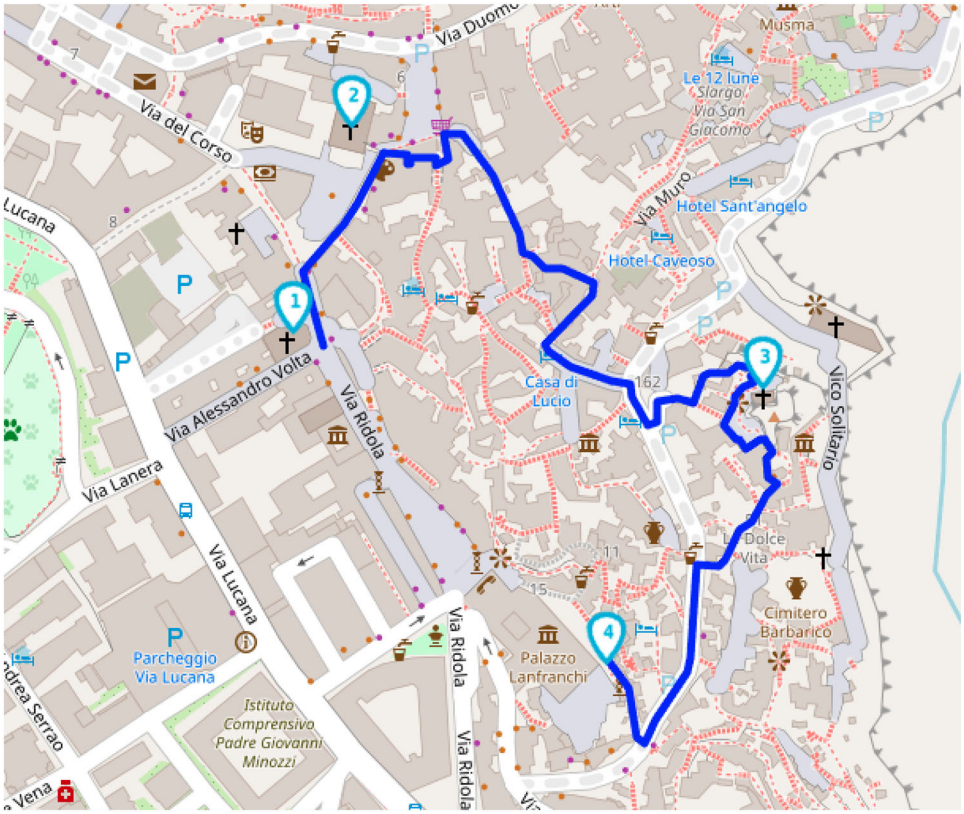

Fig. 11 Result of orienteering service for thematic tour

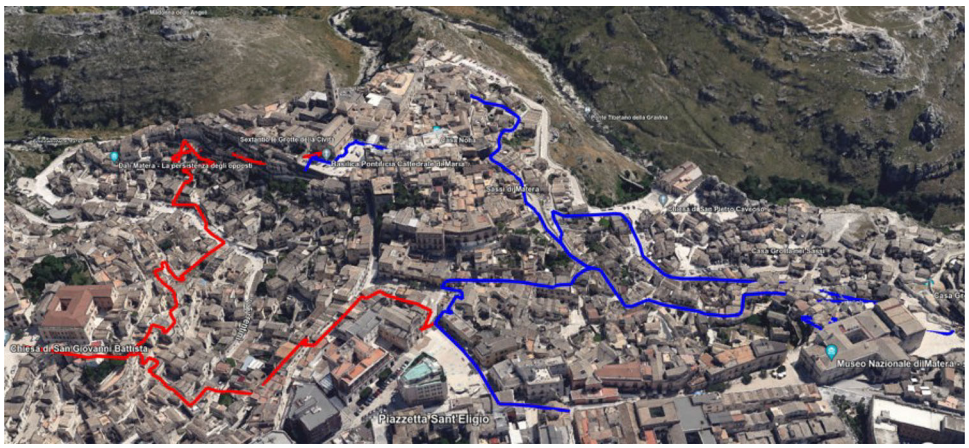

Fig. 12 Comparison with in blue the tour considering slope, while in red the tour considering distance

the city, but shows its limitations in the historical centre of the Sassi, due to its complex nature of cave dwellings with overlapping levels and steep, irregular walkways. Similarly, the precision of the shadow computation is related to the quality (resolution and detail) of the geometric representation. Ongoing work focuses on improving the model with higher resolution data, either at global scale, if further data sets are made available (e.g., the original LiDAR data that produced the DSM and DTM used in this study) or at a local scale, e.g., through acquisition sessions with terrestrial or mobile scanning devices on limited areas or specific Points of Interest (see [26]). A finer morphological characterization on a more detailed 3D model will be performed by identifying, e.g., the width of streets, the slope and width of roofs, the detection and quantitative description of pavements, ramps, stairs, the identification of rough paths, etc. To improve the illumination/shading service, ongoing work aims at integrating sky coverage information to provide an estimate of the solar radiation received per unit area, to support energetic considerations.

A network of smart cameras and sensors is currently being developed within the city for the monitoring of the vehicle and pedestrian traffic volumes, and environmental monitoring. An optimal distribution of the smart cameras and sensors

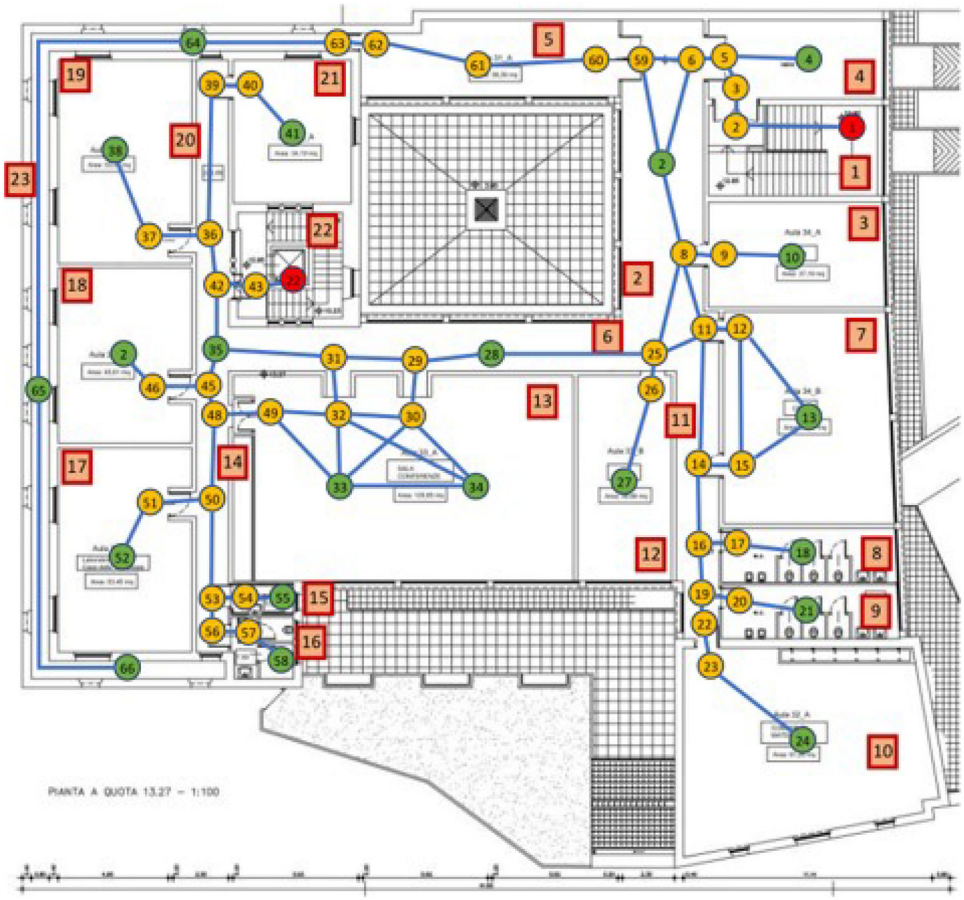

Fig. 13 The graph $G = (V, A)$ that models the IV floor of Hub San Rocco

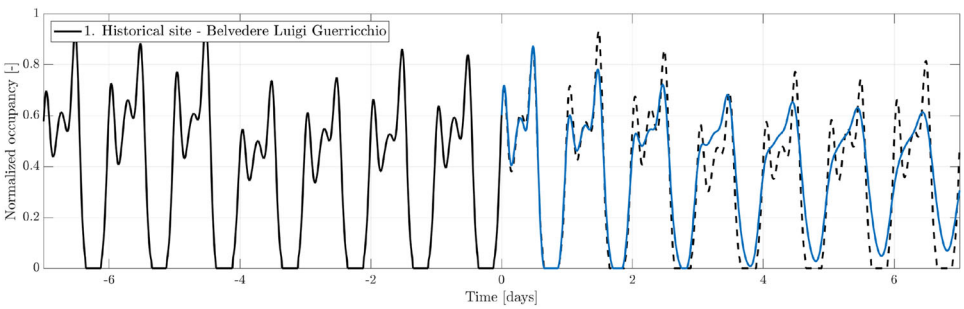

Fig. 14 Detail of a synthetic occupancy history and prediction (forecasting)

is identified considering their accuracy and capability within the urban, morphological, and architectural context.

Concerning the participatory data collection process, it is performed by using a PPGIS webtool. Future developments will concentrate on: enabling the synoptic and interactive visualization of data directly on the 3D model of the city; post-processing the community dataset in order to detect patterns related to spatial behaviours and trends; matching participatory data with other data sources in order to foster cross-learning; suggesting custom paths based on grassroots routes or point of interests; including participatory data in the decision-making workflow, so to enhance its overall sensing/cognitive process both in terms of available information about objects (e.g., direct feedbacks) and relations (e.g., behavioural patterns, emotional backgrounds, perceived priorities, urban qualities and security).

A Data Lake is developed to allow data collection from the UDT modules, smart cameras, and sensors. The Data Lake allows the aggregation and extraction of information, making available to all the components of the UDT the necessary data.

The Urban Sensing Engine, effectively integrates artificial intelligence reasoning forms. Future work aims at testing the system with real users belonging to the Municipality of Matera to the refine existing rules and identify new useful ones for both by the reactive and the deliberative components.

The optimization methods demonstrated to be able to provide optimal path almost in real time and to able to consider

user preferences. Furthermore, the optimized evacuation path service demonstrated to be able to identify optimal paths and trapped visitors at most in 5 s.

Finally, the occupation prediction service demonstrated to be able of accurately predicting the occupancy of a generic PoI. For short term prediction (up to 24 h) the accuracy is remarkably good, with highly accurate predictions of peak values and their occurrence in time. For longer term predictions (over 24 h) the accuracy in predicting the peak is reduced but the time occurrence is still well predicted. Future work will aim at applying the ADMD to real data from sensors and exploit the mode analysis to identify the city's dynamics.

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