Urban Digital Twin for Territorial Management

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Abstract

This PhD research harnesses weather, air quality data, and walkability metrics to provide insights into urban planning's multifaceted impacts, emphasizing the importance of emergency preparedness. Despite the plethora of data, including satellite measurements, accessing it is complex due to the lack of inter-departmental collaboration, standardized data-sharing protocols, and incentives to improve data pipelines. Our efforts form foundational components of an 'Urban Scale Digital Twin', pushing the boundaries of traditional urban planning towards a more holistic, data-informed approach that encapsulates the evolving needs of urban residents. The project includes a comprehensive mapping study on Digital Twins (DTs) for city and territory management.

Keywords

Digital Twin, Software Engineering

Context: As cities grow and data availability increases, advanced technologies and methodologies offer new opportunities to enhance urban planning. This project began with an in-depth mapping study on digital twins (DTs) in urban planning, guided by broader studies on software engineering for DTs [1]. The works that leveraged open data to provide a system supporting decision-makers and citizens, e.g. [2] and [3], emphasized the importance of urban-scale digital twins for simulating environments and develop scenarios to address policy issues. They argue that for digital twins to be truly transformative, they must be deeply integrated into the governance mechanisms of cities rather than functioning as standalone technological entities. Additionally, several articles, such as [4] and [5], explore the impact on quality of life metrics and how urban spaces are experienced when a framework is in place to harness the potential of our data-driven society. The findings informed further research into key components of the ongoing PhD project aimed at creating an urban DT to guide sustainable reconstruction choices in L'Aquila and the surrounding province, we prioritized the development of a simulation toolkit for emergency preparedness and a dashboarding platform for quality of life monitoring, providing a comprehensive tool for enhancing urban planning and management (See Figure 2).

Research questions: The landscape offers an interesting case study in the context of L'Aquila, as mentioned by [2], because it is a highly seismic area with continuous reconstruction activities. ***Can urban digital twins be effectively utilized to enhance safety and the quality of life?*** Public Administrations often operate with tight budgets, limited personnel, and varying technological infrastructure, hindering the development of sophisticated, standardized data collection and management systems. In L'Aquila, effective reconstruction requires an intimate understanding of its urban fabric to prioritize safety, resilience, and the lived experiences of its inhabitants. Easy-to-setup urban digital twins (DTs) that support critical decision-making can address these needs. A major challenge in data acquisition is the lack of standardization, as each public department might use unique data formats, storage methods, or web portals. This fragmentation makes data aggregation difficult, isolating valuable information. Transparent data pipelines can promote trust and ensure data consistency and reliability, bridging the gaps identified in our preliminary mapping study (Figure 1). ***How can standardization in data collection and management be achieved across various public departments to enhance data integration and utilization?*** To address urban challenges through advanced data analytics, machine learning, and visualization platforms, this project aims at outlining a holistic blueprint on how to provide local administrations with the appropriate tools to extract values from data in regions with unique vulnerabilities. The meticulous data preprocessing methods employed in our approach ensure

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the accuracy of the resulting dashboards, which is pivotal for any urban planning decision in such vulnerable territories. This project seeks to develop a comprehensive strategy that spans multiple public departments, promoting standardization and seamless data utilization across various platforms. ***What approaches can be developed to equip local administrations with tools for disaster preparedness?*** The project investigates the development of a simulation toolkit for disaster preparedness that surpasses existing solutions by utilizing open-source tools and flexible data inputs. The toolkit is designed to be interactive and customizable, with many settable parameters, making it adaptable for various personas and scenarios. Unlike previous studies, which often provide static or narrowly focused tools, this project aims to create a dynamic and multi-persona toolkit that enhances collaboration and preparedness at the local administration level. The focus on open-source tools and optional data inputs ensures broad accessibility and applicability, addressing gaps in current disaster preparedness methodologies.

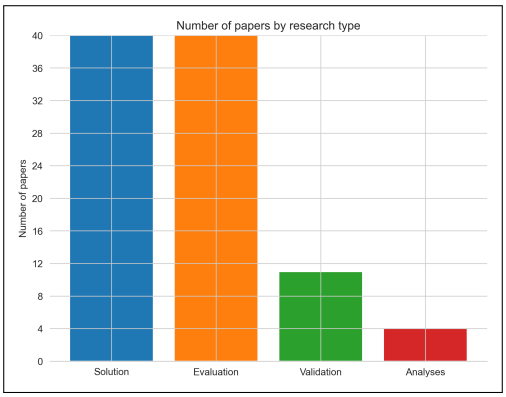

Figure 1: Preliminary results of our Mapping Study on Software Engineering for Digital Twins showing a gap in validated and fully implemented solutions.

Methods and evaluation: To address these research questions, we combined data visualization, automated data extraction, and comprehensive data preprocessing as partially outlined in Figure 2 and described in this section. We automated the extraction of information from reputable Public Sector data lakes (Data Gathering Figure 2) without manual intervention, ensuring the comprehensiveness and reliability of our dataset. Key datasets included: Reconstruction Data-sets from USRA and USRC, providing information on post-earthquake reconstruction activities; Air Quality Data-sets from CeTEMPS, ARPA, and ESA, offering insights into air quality through high-resolution pollutant measurements and weather summaries; Walkability and Service Accessibility Dataset, developed by ESA and local entities, evaluating pedestrian-friendliness and service accessibility in urban areas. In urban environments, variations in aerosols were measured using satellite data and on-the-ground measurements, serving as an indicator for air quality assessment. The larger goal was to develop a dashboard for city sustainability indices, providing real-time information about air quality and its impact on public projects and emergency situations. Preprocessing the diverse data involved data pivoting, imputation, and normalization to ensure consistency, quality, and usability. Challenges included temporal and spatial granularity differences, inconsistent data formats, missing values, and differing units. Accurate merging required sophisticated algorithms, domain expertise, and iterative refinement using Python libraries (Preprocessing Phase Figure 2) Data interpolation using Machine Learning models helped to produce reliable sustainability dashboards in areas less covered by sensors, we then overlayed a mapping schema with intuitive aliases and comprehensive explanations. Plotly and Grafana have been interchangeably used depending on the plotting requirements and the resulting dashboards are easily deployable on SoBigData [6], an existing a National Public Research infrastructure and communicate insights to stakeholders involved in urban sustainability projects. On the simulation side instead the methodology essentially follows a 5-steps path: the setting up of the knowledge system (e.g. GIS Data alongside emergency plans), the choice of the case study to scope its validation, the construction of the software simulation tool realised with the open source GAMA platform [7] and its application to the the case study, the definition of alternative scenarios with the application of safety-based urban design

techniques and the related application of the simulation to check the degree of optimisation achieved.
Preliminary results: Our primary analytical approach employed Exploratory Data Analysis (EDA) techniques to unearth patterns and correlations within the datasets. For instance, we analyzed the impact of weather conditions on air quality, highlighting discernible trends (refer to Figure 2). The data shown is part of our data lake, showcasing correlations between walkability and public spending, mean temperature trends, and the impact of weather conditions and construction work on air quality. By juxtaposing air quality, walkability, and emergency response metrics on interactive dashboards, we foster a culture of informed decision-making and proactive urban planning among citizens and stakeholders, contributing to urban sustainability and data-driven policymaking. Feedback from stakeholders and users was incorporated to refine the tools and improve their usability and impact. Regarding

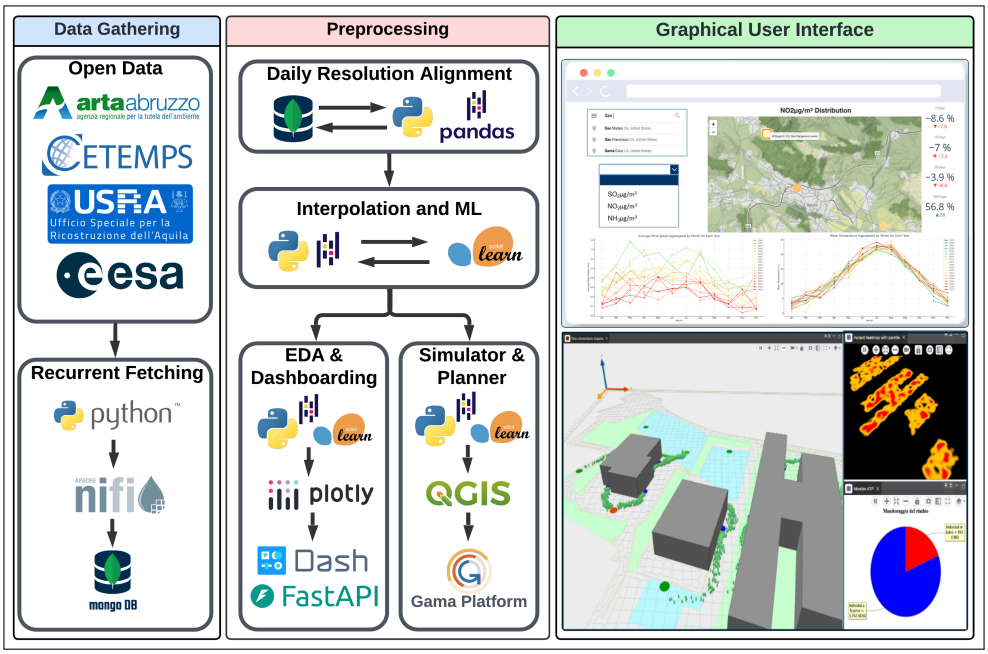

Figure 2: Technological View of the proposed Urban Digital Twin

the simulation tool, our research demonstrated the significant usefulness of software simulation tools combined with urban design techniques for optimizing urban contexts and increasing urban resilience. In particular, the optimization of the emergency area system performed for stakeholders working at civil protection facilities expressed great interest in deploying the simulator.
Discussion and future work: Overcoming human bottlenecks in public sector data gathering remains a challenge, as web portals are sometimes updated with delays of up to six months. For public administrations with limited resources, automating this process is cost-effective and ensures a consistent flow of accurate, up-to-date information. Implementing thematic dashboards can enhance citizen engagement by providing real-time, easily interpretable data, aiding in better decision-making so future work will consist in integrating systems for automatic alerts and actionable items within the platform. On a more specific note, during emergencies, real-time data availability is crucial. And simulators like the one proposed [8] can help on this front but the use of real-time sensors data for crowd monitoring is a much needed improvement. While the challenges posed by public administration constraints are genuine, they can be mitigated with the right technological solutions improving urban management and quality of life.
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