Digital Twin as a Tool for Participatory Cultural Heritage Regeneration: The Case of Pavia Historical Urban Center in Italy

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Abstract. This paper presents ongoing research developed within the project entitled *Digital Modelling to Support the Design of Safe, Sustainable and Resilient Environments* of the Department of Excellence 2023–2027 in the Department of Civil Engineering and Architecture of the University of Pavia. The main aim of this paper is to develop an investigation on the application of digital twins in historical cities to implementing a specific application scenario for the city of Pavia. The adopted method is based on an exploratory qualitative approach that is not only interpretative, but above all proactive and projective. The results obtained highlight the possibility of applying digital twins as an important tool that can combine adaptive regeneration design in medium-small sized historical urban centers such as the city of Pavia, balancing the needs of heritage protection with those of sustainable transformation, participation and inclusiveness.

Keywords: Digital Twin · Cultural Heritage · Urban design · Historical Urban Centers · Environmental design

1 Introduction

Digital twins (DT) have recently undergone a significant evolution, extending the opportunities for their use in the urban context, with relevance in historic centers. In those contexts, characterized by high morphological complexity and cultural heritage, the integration of multisensory data, 3D modeling and predictive techniques opens new perspectives for all the actors involved in the urban development: from urban and architectural design to monitoring and adaptive management of heritage. However, their application raises critical questions about data interoperability, representative accuracy and sustainability of digital workflows. Furthermore, the use of interactive platforms enhances participatory design, but requires new forms of governance and epistemological inclusiveness [1–4].

Although digital twins were initially developed for industrial applications, their use has rapidly extended to the urban environment, attracting growing interest, especially in historic centers, where conservation challenges intertwine with those of adaptation [5].

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Therefore, digital twins are establishing themselves as innovative and strategic tools for planning, urban and architectural design, as well as for city management. In short, they can be described as virtual replicas of physical systems, capable of integrating real-time data, simulations and advanced analyses, in order to design processes as well as support decision-making [6].

Nevertheless, the application of digital twins' tools and platforms in historic urban contexts brings specific challenges and opportunities, different from modern urban environments. Historic centers such as the city of Pavia preserve invaluable cultural assets that require targeted approaches for monitoring, conservation, regeneration and adaptive design, supported by intelligent management. Furthermore, integrating heritage protection within digital twin frameworks implies an interdisciplinary collaboration between planners (urban planners, architects, designers), conservation experts, data scientists and local stakeholders [7]. Implementation of digital twins for application in historical urban centers is based on the integration of a structured set of technologically advanced operational tools that consequently involve the adaptation of new operational workflows. Data collection is delivered to high-precision acquisition technologies, such as 3D scans using LiDAR, photogrammetry and geo-radar, which allow obtaining extremely detailed digital representations of historical buildings and urban fabrics, detecting complex geometries and material conditions with high accuracy [8]. In support, IoT sensor networks monitor environmental and structural parameters in real time – such as temperature, humidity, vibrations and tourist flows – using non-invasive methods, which are essential for the protection of architectural heritage [7]. Three-dimensional simulations, based on tools such as computational fluid dynamics, finite element analysis and agent-based modeling, allow us to anticipate the impact of events and interventions on structures [6]. Finally, artificial intelligence and machine learning offer predictive and diagnostic tools for both conceptualization of design strategies and the revealing of anomalies and maintenance management. Furthermore, digital twin applications for cultural heritage offer a wide range of strategic advantages. For example, the permanent monitoring and real-time simulations allows to rapidly identify structural problems, humidity phenomena or material degradation processes [5]. Predictive simulations also allow to evaluate the effects of environmental factors such as climate change, pollution and overtourism pressure, providing effective bases for mitigation strategies [7]. As well as virtual environments allow to test design interventions in a safe way, while high-definition digital models contribute to accumulate endless material for documentation, preservation and so doing the protection of historical memory of a place [6]. Finally, one of the most relevant contributions offered by digital twins is their potentiality to strengthen participatory processes within historical urban contexts. Through interactive visualization platforms, it is possible to actively involve residents, business operators and tourists, offering them direct access to data and scenarios of urban transformation [9, 10]. This approach facilitates the co-creation of knowledge, combining technical skills with local knowledge for a shared and complex reading of the places [11]. Furthermore, decision-making transparency is improved thanks to the possibility of clearly visualizing the consequences of design choices, promoting a more inclusive urban governance [8]. However, it is necessary to keep in mind that the success of such practices requires solid governance, active community involvement and integration with existing practices [12].

Within this framework, the research question might be: How can digital twins contribute to adaptive conservation and design in small-medium sized historical urban centers such as the city of Pavia, balancing the needs of heritage protection with sustainable transformation and inclusive participation?

To answer this research question, this paper proposes to adopt an exploratory qualitative approach, based on a comparative documentary analysis of case studies relating to the use of digital twins in some European and non-European historical cities. The aim is not only interpretative, but above all proactive, aimed at developing a feasible scenario for the city of Pavia. The framework in which this research has been developed is on the one hand the Dorian project (Digital Modeling to Support the Design of Safe, Sustainable and Resilient Environments) which is a project of the Department of Excellence 2023–2027 of DICAr (Department of Civil Engineering and Architecture of the University of Pavia), on the other the experience gained within international collaborations between the University of Pavia and Tongji University and which allowed the authors to directly observe the installation, implementation and application of the CityScope platform jointly developed by the City Science Lab of MIT and the College of Design and Innovation of Tongji University in Shanghai. The full work package developed in the CityScope @Shanghai project is the main background on which the following research phases have been developed: 1) the selection of case studies, 2) the thematic matrix for the comparative analysis of the selected case studies, 3) the scenario design in which a preliminary project proposal for the city of Pavia is developed.

Consequently, this article is set out as follows: first, after a brief introduction, an overview of the MIT-Tongji CityScope Project in Shanghai is developed, summarizing the results and lessons learned but above all the correlations that CityScope can have in historical urban contexts such as Pavia. Second, a comparative synthesis of five international case studies is developed with a particular focus on the contextual adaptations of digital twins in urban and historical contexts. Third, a SWOT analysis of the application of digital twins to historical urban centers is developed. Fourth, based on the entire body of knowledge developed in the previous phases, a proposal of the Digital Twin application to the urban context of Pavia is delivered. Finally, the research outcomes are critically discussed.

Please note that the first paragraph of a section or subsection is not indented. The first paragraphs that follows a table, figure, equation etc. does not have an indent, either.

Subsequent paragraphs, however, are indented.

2 The MIT-Tongji CityScope Project in Shanghai

2.1 Overview of CityScope Shanghai

CityScope Shanghai is a platform developed by MIT City Science Lab and jointly applied at the College of Design and Innovation of Tongji University. It is a pioneering application of interactive digital twins for participatory urban design. Although not specifically designed for historical contexts, the project stands out for both its technical format and the methodologies used, which have a high potential for adaptation to decision-making processes related to the protection and enhancement of cultural heritage.

The platform operates through an interactive augmented reality system, which simulates the impact of emerging urban design solutions and technologies on the built environment. It integrates physical models, projective mapping, sensor networks and advanced computational simulations, configuring a dynamic environment that facilitates shared design experimentation [13].

Its application in the Siping Road district in Shanghai represents a fundamental example of the use of digital twins to support inclusive decision-making processes in urban design and planning. In this context, CityScope has demonstrated a remarkable capacity for integrating physical and digital representations: real-time data, combined with simulation results, are projected onto physical models of the area, thus enhancing the interaction between users and the system. The interface, based on LEGO components, allows stakeholders to physically manipulate urban elements and immediately visualize the effects of changes [14].

The system also uses a complex layering of data that includes real-time traffic flows, building morphologies, land use patterns, socio-economic and environmental indicators (such as air quality and noise levels), as well as energy parameters. This information set allows the modeling of complex urban scenarios, including the management of pedestrian flows, the reconfiguration of public spaces, the optimization of green infrastructures, the modification of transport networks and the experimentation of mixed-use urban development schemes.

CityScope is also configured as a collaborative decision-making space, where public administrators, designers, residents and other stakeholders can discuss design solutions in a shared environment, iteratively improving proposals based on generated data and simulations [15, 16].

2.2 Results and Lessons Learned and Correlation with Historical Urban Contexts

The experience of CityScope applied to the Siping Road urban community has highlighted significant results. The visual and tangible component of the platform has encouraged public participation, overcoming the typical barriers of traditional decision-making processes. The possibility of visualizing the impact of designed project in real time has allowed to revise and implement the project proposals based on evidences, making possible to achieve at least two very important results that we believe are relevant for the purpose of this research: 1) facilitation of solutions partially or totally already discussed and shared with the inhabitants of the community, 2) revision and refinement of the project proposals on visible data, allowing to avoid project compromises that would have reduced the effectiveness of the project itself. This was possible by having the opportunity to visualize and explain the projects to the inhabitants in advance and therefore putting them in a position to evaluate the best available solutions, thus avoiding choices oriented to individual interests. Therefore, CityScope has made clear the importance of integrating advanced digital technologies and the social dimension, highlighting once again how the human component and the active involvement of citizens is essential for the success of digital innovations.

Finally, taking into account the aim and the research question of this study, it is necessary to mention the fact that the morphological, architectural and cultural heritage

characteristics of the urban area of Siping Road in Shanghai are different from the historical centers of European cities. Siping Community is a complex, active and thriving urban context. Located in the Midwest of Yangpu district of Shanghai, it is 2.75 square kilometers in area and has a population of over a hundred thousand. Siping community includes one of Shanghai's first workers village called Anshan village. It was built in the 50's of last century and become one of the largest villages in Shanghai at that time. After continuous expansion, it now includes 8 villages. In the community, two thirds of the buildings recognized as an old community due to housing condition, outdated infrastructure, and lacking quality in public space, and the neighborhood looks less vital and strength. But at the same time, there are lots of leftover space and hidden space that are not well used and are ready to be converted [17, 18].

Nevertheless, the solutions and results achieved with the CityScope can also be applied to contexts such as the historical center of Pavia if consciously adapted with respect to at least three themes: 1) the symbolic value and memory of urban spaces and architectural elements, 2) cultural and identity aspects of local communities, 3) the morphological, material, visual and perceptive complexity of the urban environment. Once again, from a design point of view, the context, understood in its broadest expression of a set of physical or environmental elements and meaning, remains of fundamental importance even in the application of digital technologies that do not yet seem to be able to grasp the urban environment semantic as well as its symbolic cultural depth [19].

3 Selected Case Studies: Contextual Adaptations of Digital Twins in Urban and Historical Contexts

The following selected five case studies were chosen with the aim of representing a variety of approaches, scales and purposes in the adoption of digital twins in European and non-European urban contexts. These examples underline complementary application scenarios: from the preservation of cultural heritage in vulnerable historical environments, to the promotion of civic participation, and yet to resilient urban design and planning. This heterogeneity it is not diriment for our research scope but in the contrary allowed us to explore in a comparative method the potential and challenges of transferability of this technology, providing a complex framework useful for adapting the model to the case of Pavia.

In the current wide spectrum of urban applications of digital twins, the city of Venice represents for our study one of the most representative cases in a historical context. The initiative promoted by Venice municipality is motivated by the need to respond to exceptional conservation challenges that characterize Vencie itself, linked to the hydrogeological vulnerability of the city and the pressure exerted by mass overtourism. The developed system integrates a plurality of data in real time: from sea level rise to the structural settlements of buildings and tourist flows. This technological infrastructure has proven to be particularly effective in balancing the needs of heritage protection with those of contemporary fruition, outlining new models of adaptive urban governance [20].

In Herrenberg, a German town located in the metropolitan area of Stuttgart, the use of the digital twin has focused on issues related to urban mobility and air quality. Thanks

to an interactive platform that combines digital simulations and immersive virtual environments, the city promoted a participatory decision-making process, actively involving citizens and local stakeholders in the co-creation of scenarios for traffic management and environmental sustainability. The small scale of the context favored a high and quick responsiveness between technologies, communities and urban policies [21].

The Amsterdam Time Machine case instead adopts a deeper historical perspective, developing a digital twin that integrates ancient maps, archival documents sources and three-dimensional models to trace the urban evolution of the city over the time. This "four-dimensional" approach allows not only to explore the urban past, but also to understand how historical dynamics influence the contemporary spatial urban structure. The project is a valuable resource for architects, planners, historians and citizens interested in a layered narrative of urban development [22].

The city of Zurich offers another example of a long-term application of digital twins in the urban sphere. Perhaps the most developed in Europe, since the 1990s, the city has started a progressive process of digitization of spatial data, culminating in 2011 with the creation of an integrated three-dimensional urban model. Currently, the digital twin of Zurich serves as an operational tool to address complex urban planning challenges, modeling future scenarios through the combination of geospatial data, simulations and intuitive visual interfaces [23].

Finally, the project developed in New Orleans after Hurricane Katrina demonstrates the application of digital twins in contexts of climate vulnerability and cultural heritage. Focused on the historic neighborhoods of the French Quarter and the Garden District, the system integrates predictive modeling for floods, structural monitoring of historic buildings and heritage protection strategies. This case study, despite of being not an European case provide a meaningful insights for our study. In fact, the New Orleans platform contributes substantially to the construction of a data-driven urban resilience, oriented towards prevention and safeguarding the city's identity [24].

By deploying a comparative analysis of the five case studies clearly arise how digital twin technologies share a common infrastructural basis – consisting of 3D models, real-time data integration and predictive simulation capabilities – but require careful adaptation to local specificities. The experiences of Venice and New Orleans show an application oriented towards heritage protection in contexts at environmental risk, while Herrenberg and Zurich focus on sustainable planning and urban management through participatory models. Amsterdam, on the other hand, is an outstanding example for its strong historical-cultural and temporal vocation. In all cases, the effectiveness of digital twins depends on their ability to interface with designers, governance, the needs of local communities and the constraints imposed by cultural preservation. The following Tables 1 and 2 represents respectively, highlight of the objectives, technological approaches and distinctive features of the projects analyzed and, the SWOT analysis of the application of digital twins to historic urban centers.

Table 1. Comparative analysis of the five case studies

Case Study City	Main Objectives	Technological Approach	Distinctive Elements
Venice, Italy	Tourism management and adaptation to climate change in a fragile historic context	Integration of real-time data: water levels, structural stability, tourist flows	Holistic system for heritage conservation and environmental monitoring
Herrenberg Germany	Reduction of urban congestion and improvement of air quality	Immersive simulations and virtual reality for co-design	Active citizen involvement in a transparent decision-making process
Amsterdam, Netherlands	Study of historical urban evolution and informed planning	3D modeling and digitized historical maps (4D approach)	Strong archival and temporal component to understand urban changes
Zurich, Switzerland	Support for urban planning and sustainable management	3D urban model with integrated geospatial data	Long-term experience with progressive urban digitization
New Orleans, USA	Strengthening urban resilience in historic neighborhoods after disasters	Predictive simulations for floods and structural monitoring	Focus on protecting cultural heritage in vulnerable areas

4 Application of the Digital Twin to the Urban Context of the City of Pavia

4.1 The Urban Heritage of Pavia: A Layered Context

Located in the Lombardy region, in northern Italy, Pavia is an emblematic case of a medium-small sized European historical city, whose urban settlement reflects a thousand-year-old stratification. Founded as a Roman settlement, the urban morphology in the central area preserves a historical road network characterized by orthogonal blocks, which integrate the medieval layout and subsequent additions. Significant architectural elements include monuments, towers, palaces and the large historical complex of the University – among the oldest in Europe – the Visconti Castle and numerous historic churches. The city also features a strong integration between the urban and natural landscapes, highlighted by the relationship between the historical center and the Ticino River, with iconic elements such as the Ponte Coperto as well as the evident correlation with the surrounding agricultural landscape with the Cascine farmhouse and the water network infrastructure of the hundreds of creeks and the water canal Naviglio Pavese. Along with this physical context the city presents social dynamics embodied by traditional practices, but above all by a lively student population. Considered as a whole,

Table 2. SWOT analysis of the application of digital twins to historic urban centers

Strengths	**Weaknesses**
– Real-time and holistic monitoring of historic centers, with predictive capabilities and dynamic temporal analysis – Objective decision support, increased transparency, and public participation through interactive visual tools – Integrated management of physical components and cultural practices	– High costs for technologies and specialized skills – Lack of complete historical documentation – Technical integration difficulties among heterogeneous systems – Regulatory limitations for sensor installation and privacy-related issues
Opportunities	**Threats**
– Growing political support and access to European and international funding – Potential to enrich the tourist experience with immersive technologies – Effective tools for climate resilience and adaptive planning – Promotion of interdisciplinary synergies among technology, conservation, and planning	– Risk of marginalizing traditional skills – Digital accessibility barriers for certain segments of the population – Uncertainties about long-term sustainability and data security – Doubts regarding the authenticity of digital representations

these characteristics are imposing specific requirements for the implementation of a digital twin, profoundly different from those of large modern cities [25, 26]. Based on the literature analyzed and international case studies, a modular and progressive approach is proposed for the introduction of a participatory digital twin in the city of Pavia, divided into three main phases: 1) data collection and infrastructure construction, 2) development of an interactive platform, and 3) simulation of scenarios for decision support.

4.1.1 Digital Workflow

The first phase is suggested involves the collection of data on urban heritage using non-invasive IoT sensors, capable of monitoring environmental conditions in historic buildings (temperature, humidity, vibrations), supported by mobile technologies and citizen science tools, to limit direct intervention on protected structures. This is coupled by three-dimensional documentation through photogrammetry and laser scanning, integrated with digitalized historical sources such as maps, photographs and archives. These data feed a multi-level platform that organizes information relating to architectural heritage, environmental context, mobility and land use patterns, as well as management and protection activities. The technological structure is based on a scalable cloud infrastructure, enhanced by edge computing nodes for sensitive areas, and accompanied by Application Programming Interfaces (API) for interoperability with the physical world at local, regional and national systems [27].

4.1.2 Participation and Interactive Design

A key component assumed at the beginning of our research is the implementation and the involvement of local stakeholders, including conservation bodies, public administrations, citizens, universities and tourism operators [28]. The adoption of inclusive participation strategies, with particular attention to potentially excluded groups, is essential to ensure legitimacy and effectiveness. The development of multimodal interfaces aimed at both experts (GIS tools and 3D analysis) and residents and visitors (mobile applications, augmented physical models, virtual and augmented reality experiences) can be visualized as the LEGO model earlier described for the CityScope Shanghai [13]. These tools should ensure accessibility for users with different digital abilities and skills, and promote participation through continuous feedback mechanisms, gamification elements and digital forums integrated with official decision-making processes.

4.1.3 Scenario Simulation and Support for Urban Governance

The platform should integrate advanced simulation capabilities to assess the effects of urban planning and conservation interventions, such as traffic reorganization, tourism management, climate adaptation, restoration and adaptive reuse of buildings, as well as improving the quality of public spaces. The adoption of multi-criteria analysis tools will allow balancing conservation, social, environmental and economic objectives [29]. Furthermore, dynamic dashboards, early warning systems for environmental threats and visual communication tools will allow to translate technical outputs into operational knowledge for public decision makers and citizens.

4.2 Specificity and Adaptation of the Digital Twin for Pavia

As earlier mentioned at the Sect. 2.2, the application of the digital twin in Pavia should take into account some specific characteristics that, in our opinion, should be considered crucial to any urban project:

- The landscape: the origin of the city is fully intertwined to the relationship with the Ticino River. The river represents an essential landscape element but can also represent a vulnerability in hydrogeological and environmental terms.
- The morphological dimension of the historic center, although of great value, is coupled by its limited spatial dimension that requires the adoption of sustainable solutions to be activated progressively also through pilot projects.
- The tourist dimension potentiality is not yet adequately developed. If on the one hand it is hoped to avoid the crystallization of the historic center for purely tourist purposes, on the other hand the application of the digital twin could contribute to greater visibility in the national and international tourist panorama of the city as well as contribute to the adoption of effective and sustainable promotional techniques.
- The presence of the University as an institution – among the oldest in the world – offers humanistic and scientific competences that could be strategic for the sustainable development of the city.

In conclusion, the adoption of a digital twin in Pavia represents an opportunity to combine the preservation of cultural heritage along with technological innovation

and social engagement. The approach we propose, which is based on the qualitative interpretation of empirical data acquired from the critical analysis of the best international practices applied to local contexts, has set itself the main objective of enhancing the historical-cultural identity of the city of Pavia through the application of a possible, effective and efficient holistic project capable of addressing contemporary challenges related to sustainability, urban resilience and inclusiveness in its broadest sense [30, 31].

5 Discussion, Critique and Conclusion

This study was developed within the project entitled Digital modelling to support the design of safe, sustainable and resilient environments of the Department of Excellence 2023–2027 of the DICAr (Department of Civil Engineering and Architecture of the University of Pavia). The main purpose of this paper is to develop an investigation on the application of digital twins in European and non-European historical cities aimed at developing a specific application scenario for the city of Pavia. The adopted method can be traced back to an exploratory qualitative approach that is not only interpretative, but above all proactive, based on the experience acquired by the authors in other contexts within the cooperation between the University of Pavia and the Tongji University of Shanghai. The results obtained, which will have to be implemented in the continuation of the research, highlight the possibility of applying digital twins as an important tool that can combine adaptive conservation and design in medium-small sized historical urban centers such as the city of Pavia, balancing the needs of heritage protection with those of sustainable transformation, participation and inclusiveness.

Beside encouraging results achieved in terms of innovation and development prospects, the approach reveals inevitable critical issues and limitations.

First, if on the one hand, it may seem redundant to highlight that the integration of digital twins in small and medium-sized historic urban centers such as Pavia, represents an emerging and fundamental frontier as also affirmed by the EU's Digital Strategies for Smart Cities and Communities in Europe [32] in the field of urban design and planning it pave the way to new perspectives as it integrates multidimensional data, advanced high-quality 3D modeling and predictive techniques to support effective decisions. On the other hand, it is not obvious to highlight again what we can define as the contextual adaptation of technological innovation. In fact, for the city of Pavia, characterized by a layered historical, cultural, morphological complexity, a progressive and modular approach is proposed, based on the structured collection of data, the development of an interactive platform and the simulation of future scenarios fully incorporated into the context, understood in its broadest expression as a set of physical or environmental elements and of identity meaning.

The contextual adaptation of this approach is even more fundamental if the aim is also to adopt inclusive participation practices, which can guarantee a broad social sharing of the proposed solutions.

As a consequence, if this technology opens new perspectives for the management and sustainable development of cities, at the same time it raises crucial questions related to the interoperability of systems, the accuracy of the information collected, the long term sustainability of digital infrastructures and the digital literacy of the broadest spectrum

of the population. In this context, the interactive platforms studied and analyzed in other research, such as the CityScope developed by MIT and Tongji University in Shanghai, demonstrate how such integration can facilitate shared decision-making processes and improve the understanding of urban phenomena. However, the transfer of these models to different contexts, such as European historic centers, requires specific adaptations. The analysis of five case studies, four of which are European case, ranging from the conservation of cultural heritage to the promotion of urban resilience, highlights the potential and critical issues of such adaptations. The critical element that emerges from these experiences is the pulverized or ultra-specialized application of these technologies and that in this research it is suggested to avoid for the scenario of the city of Pavia.

In conclusion, for urban realities such as Pavia, the digital twin cannot constitute a tout-court solution that is based exclusively on the application of advanced technologies but rather highlights the need to integrate a set of tools that, if adopted with awareness and competence, can facilitate new opportunities for urban design and planning, participation and sustainable management of the urban and architectural heritage. In this sense, these tools will be able to connect human intelligence and represent a bridge between the memory of the past and the challenges of the future, advancing the construction of more aware, resilient and inclusive historical cities.

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