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# Developing of a Digital Twin for Urban Planning in an International Context

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**Abstract:** The digital twin, adapted to the needs of urban planning and monitoring systems, is the subject of research and development in the academic, commercial and public sectors. The article provides international context in conceptual and practical implementation through their maturity level, scope, purpose, structure, input, processing features and output. The City of Zagreb is presented as an example of the implementation of GIS and 3D city models in urban planning, with activities towards a digital twin city. Based on research and local specifics, the concept of a digital city twin was proposed for the needs of urban planning, and future challenges were identified.

**Keywords:** digital twin; City of Zagreb; international context; urban planning

## 1 INTRODUCTION

The digital twin, adapted to the needs of urban planning and monitoring systems, is the subject of research and development in the academic, commercial and public sectors. To develop such a complex tool for urban planning, many aspects need to be explored and fulfilled.

Urban planning and monitoring systems traditionally use a wide variety of spatial data sets. Data management, analysis and creation have evolved from analogue techniques to 2D GIS and 3D city models. The next step is to build digital twins for urban planning. This can be achieved by integrating digital twins with official and real-time data and by introducing improved analytical and simulation models into them.

The digital twin city is an actual topic of many world's researchers in different aspects of purpose, structure, technology, data sources and tools. However, existing case study comparisons tend to be general and not specifically focused on the topic of urban planning and monitoring. Digital twin for urban planning and monitoring is a specific type of digital twin with specific research and development challenges and questions, considering 3D city model type and quality, government data integration, need for live data, data visualization issues, simulation issues, planning functionalities and tools.

This paper provides an overview of historical and current research on the topic, from the need for spatial data in urban planning, to the role of 3D models, and finally the transformation into digital city twin.

Selected international digital city twin projects and initiatives are used as a background to define the characteristics of a generic digital city twin for urban planning.

The new Zagreb digital twin was proposed on the basis of a generic model, existing achievements in the use of 3D city models for urban planning, and local specificities.

## 2 SPATIAL DATA FOR URBAN PLANNING

The basis for urban planning and monitoring system are quality and up-to-date spatial data and information, managed by geoinformation systems and technologies. In urban planning systems, spatial data on city's present and past is used to transform goals and objectives of society into formal urban plans and documents. Urban monitoring systems uses real-time spatial data to monitor and supervise practical implementation of urban plan regulations [1] (Fig. 1).

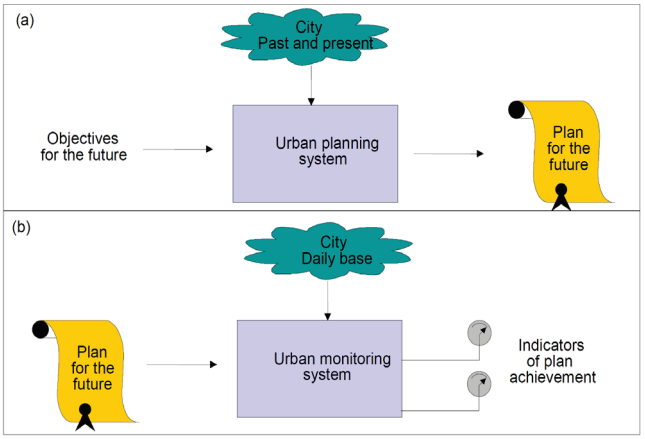


**Figure 1** Urban planning and urban monitoring system [1]

The process is also seen as a spatial planning cycle, which consists of [2] (Fig. 2):

1) spatial policies
2) implementation
3) monitoring and evaluation.

According to [3], spatial information analysis and spatial planning are part of a wider land management system. Society's needs and spatial information are the basis for decision-making on the general goals of land development. These goals are the input for the spatial planning system, followed by implementation measures and monitoring of practical results.

Urban planning uses a wide range of spatial data and information during the analytical phase. These data come from several professional areas, e.g. [4, 5]:

- topography
- hydrology
- geology

- climate
- vegetation
- infrastructure
- land use
- land cover
- demography
- economy
- housing, etc.

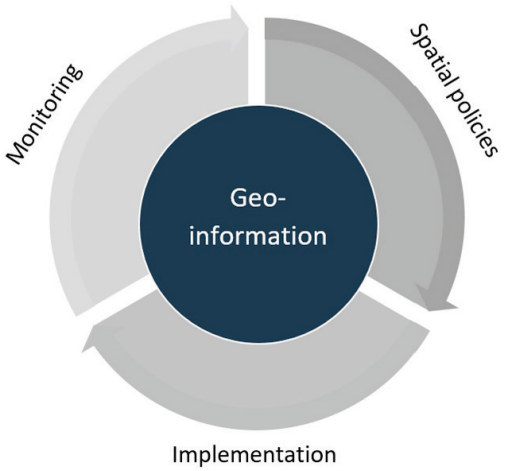


**Figure 2** Geoinformation and spatial planning cycle [2]

In a narrower sense, the urban planning and monitoring system focuses on creating and implementing of land use plans and monitoring of land use changes.

## 3 THE ROLE OF 3D MODELS AND DIGITAL TWINS IN URBAN PLANNING

With the development of geospatial technologies in the collection, processing and visualization of spatial data, the next step was the creation and use of 3D models of cities in urban planning. The main advantages of the use of 3D models were new visualization and analytical tools, such as [6]:

- overlay of 3D model and 2D land use maps
- 3D visualization of urban plan regulation scale
- 3D visualization of proposed buildings purpose
- 3D visualization of urban greenery structure
- 3D measurements and quantifications
- shadow analysis
- line of sight analysis
- 3D visualization of statistical data
- photo visualization etc.

The transformation from traditional cities to smart cities has brought forward new urban development requirements that can be supported by emerging technologies. The emerging field of City Digital Twins has advanced with the help of digital infrastructure and technologies connected to the Internet of Things (IoT) [7]. The collection of spatial data and the creation of a 3D city model are recognized as two initial phases (out of six) in the development of a complete digital city twin [7, 8] (Fig. 3).

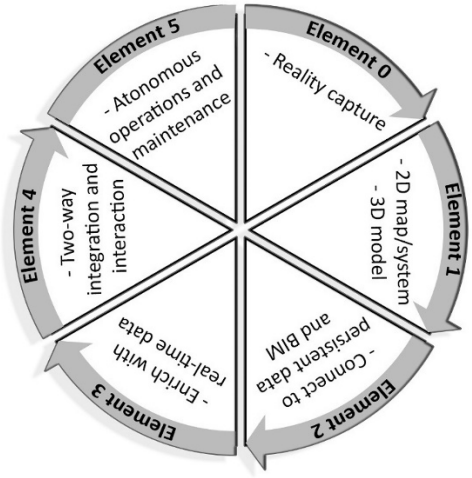


**Figure 3** Digital twin maturity levels (elements) and descriptions [7]

In the scientific and cultural debate of the discipline of urbanism, the concept of the digital twin applied to cities, sustainable urban policy development and governance is currently one of the most discussed and cutting-edge topics [9], although the topic has been experimented mainly in scientific fields of geomatics and information technology.

The field of urban planning needs specific spatial tools for urban change detection and optimization of impact of new development projects on existing urban environment. Digital city twin is viewed as a virtual 3D environment designed for urban monitoring, collaboration between different stakeholders, and practical research. Its aim is to help create cities that are more flexible, healthier, and more livable.

Digital twin characteristics are highly dependent on their use (i.e., users, lifecycle stage and application) and share few similarities, with digital model of the physical city as the foundation for other thematic modules [10].

Urban planning and asset management are recognized as the main users of the basic digital city twin model, while other main thematic modules are:

- urban mobility
- water management
- energy management
- environment and climate.

**Table 1** Example of functional and physical layers of modules for urban planning and urban mobility in the modular digital city twin concept, according to [10]

| Module | Urban planning | Urban Mobility |
|---|---|---|
| Service / actuation layer | Urban planning, asset management | Mobility management, road infrastructure, noise monitoring |
| Simulation layer | 3D visualization | Simulation, logic operation, machine learning |
| Digital modelling layer | City information model | Mobility simulation model |
| Data acquisition layer | Terrestrial/aerial imagery, cadastre, geodata, asset database | Video surveillance, microphones, public transport database |
| Physical layer | City | Private mobility, public transport, road infrastructure |

Tab. 1 shows the example of functional and physical layers of digital twin for urban planning and asset management module (user of basic digital twin model) and mobility management module (one of main thematic modules), according to [10]. Intended users of the system are public administration, citizens, asset owners, asset managers and researchers.

## 4 DIGITAL CITY TWINS IN INTERNATIONAL CONTEXT

Benchmarking of international digital city twin projects and initiatives is used as background for development of the concept of new digital city twin for urban planning. Methodology and data are based on tree relevant international studies and experiences [7, 9, 10].

Masoumi et al. from 2023 [7] compared 10 case studies from existing literature on digital twins in Europe, Asia, North and South America. Main research topics were purpose, technologies, data type and further development.

Caprari et al. from 2022 [9] analysed scientific articles on 23 digital twin projects in urban planning context from Europe, North America, Asia and Oceania. For selected 5 cities the comparison questions were digital twin type, scale, purpose, technologies, experiments, strengths and weaknesses (Tab. 2).

Ferré-Bigorra et al. from 2022 [10] made a review of 22 research papers and conference abstract on digital twins for the cities in Asia, Europe, Africa, North America and Oceania. The research was based on several indicators organized in thematic groups: application data, input data, processing data and output data.

In these studies, urban planning is recognized as one of the main beneficiaries of digital twin cities. According to [7], urban planning is the most common application by keyword search (Fig. 5), while in [10] urban planning is recognized as the second most frequent, after city management and maintenance.

**Table 2** Example of comparison of digital twins used for urban planning issues, according to [9]

| | Cambridge | Zurich, Dublin, Helsinki | Singapore |
|---|---|---|---|
| Type | Static and managerial | Dynamic-evolutive | Dynamic-evolutive |
| Scale | Supra-municipal | City, sub-areas, district | City-State |
| Purpose | Multi-level platform for cooperation between different planning levels | Data-driven preventive assessment, scenarios in sustainable urban development | Decision support platform |
| Technology | GIS-processing | GIS-BIM, Laser Scanner, UAV, IoT, | GIS-BIM, Satellite imagery, Lidar, Deep and machine learning, AI |

When it comes to [9], urban planning is the main focus of the study, with detailed subtopics such as cooperation between different planning levels, scenarios for support in sustainable urban development policies, democratisation of decision-making processes and decision support platform.

Based on research topics and case studies, main characteristics of digital twin relevant for urban planning were selected as follows:

1) **Maturity level**. 3 or more, integrated 2D, 3D and real-time data, two-way interaction
2) **Scale**. City (administrative), sub – areas, projects
3) **Purpose**. Planning support, decision support, multi stakeholder collaboration, scenarios, citizen involvement, data integration
4) **Structure**. Modular system, common digital twin platform and urban planning module as one of connected thematic modules for specific purposes
5) **Input data**. 3D city model, government data, GIS, real-time sensors, urban planning data
6) **Processing features**. 3D visualization, urban simulations
7) **Output**. 3D application, dashboard, AR/VR

Besides the recommended characteristics, practical implementation of digital city twin for urban planning have to include local specificities and user needs.

## 5 3D CITY MODEL IN URBAN PLANNING OF THE CITY OF ZAGREB

Since 2008, the City of Zagreb has been developing a semantic 3D city model. The spatial planning department was identified as the primary user and developer of the project, with additional users found in areas such as emergency management, environmental protection, energy, and heritage conservation [11, 12].

This 3D city model has been used in Zagreb's spatial planning for tasks like master and detailed planning, architectural competitions, and development within the city's protected core. In land use planning, the model helps planners verify proposed building regulations against existing conditions, making adjustments based on the heights and volumes of current structures. Additionally, the combination of land use maps and digital terrain models (DTM) aids in planning hilly or mountainous areas, taking into account terrain constraints and landslide risks.

In detailed urban planning, the 3D city model serves as a tool for assessing existing structures and for creating and presenting building regulations to the public. It allows 3D building outlines to be visualized, showing the potential future size and dimensions of buildings in a virtual environment, making it easier for both local residents and city officials to understand proposed developments (Fig. 4).

Architects were among the first to use 3D data, especially for illustrating how proposed buildings would impact their surroundings. Previously, these visualizations were created by estimating building heights and shapes without precise spatial references.

The introduction of 3D city models provided architects with these missing elements, along with the ability to integrate various spatial data. After Zagreb introduced its 3D model, architects began using it for analysis and visualization

in architectural competitions and for designing new structures in the city center (Fig. 5). This approach allows for more accurate spatial solutions and better-informed urban planning decisions.

**Figure 4** 3D interpretation of detailed urban plan overlapping 3D city model [11]

The city also plans to upgrade the 3D model to support the development of a digital city twin. The study was made in cooperation with University North, Croatia [13], with guidelines considering model types, data update methods and priorities, data sources, data integration, data formats, software technology, smart city and digital twin issues.

The latest update of the LoD 2.2 model is based on official LiDAR survey of the Republic of Croatia from 2022, and will be used as a starting point for further improvements.

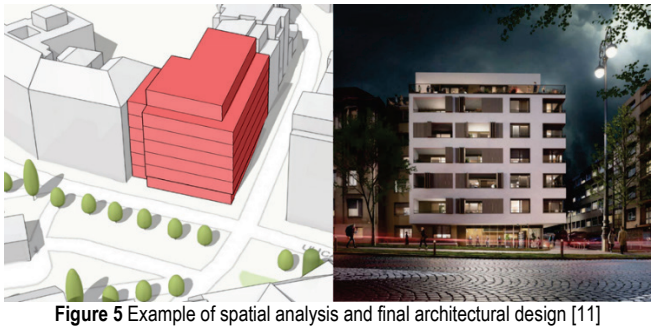

**Figure 5** Example of spatial analysis and final architectural design [11]

## 6 DEVELOPMENT OF ZAGREB DIGITAL TWIN

The City of Zagreb has started activities on the development of a comprehensive digital city twin. The initiative came as the next step after GIS and 3D model implementation in the city administration, and also influenced by development of Smart City concept and practical project implementations.

Three different city administrative units were recognized as stakeholders in comprehensive digital city twin project:

- Department for GIS and urban analytics
- Department for development of smart city
- Service for city IT infrastructure.

The role of the GIS and urban analytics department is to develop and update the 3D model of the city and all key GIS databases. In addition, their important role is the development of generic visualization and analytical features of the system. The Department for Smart Cities should define the strategic position of the digital twin in the overall strategy and activities of the smart city and coordinate the users of the digital twin within the city administration and beyond. The IT service must provide the entire IT infrastructure, with a special focus on the integration and harmonization of data sources in real time.

The City plans to develop common digital twin platform and thematic modules for specific administrative and professional needs. Based on research and previous experiences, some of the key topics were identified as city planning, environment protection, energy management, climate, urban mobility and emergency management. Besides that, modular approach gives opportunity for other thematic fields to join the project in the future.

Zagreb digital city twin platform is based on 3D city model, connected to all relevant data – city and national SDI services, national government registers, real-time data from smart city sensors and other thematic data for different uses (Fig. 6). Common digital twin platform has to provide basic 3D visualization and analytical features, while specific visualization, analytical, simulation and workflow features are planned to be developed as part of thematic modules.

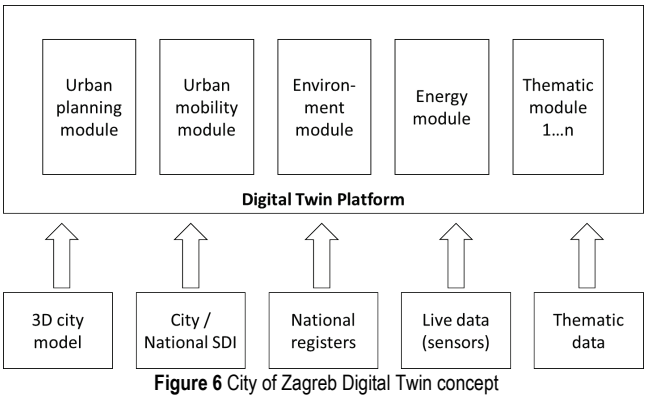


**Figure 6** City of Zagreb Digital Twin concept

Urban planning module is expected to be one of the first to be implemented, considering rich experience in using 3D model and GIS databases in that professional area. Except the user needs, modelling this thematic module must be in line with the development of national digital urban planning tools, e-Plans and e-Plans editor [14]. Urban planning module is expected to have several user groups:

- urban planners
- city administration
- architects and engineers
- academia
- civil society
- citizens.

Final visualization and analytical features of the model still must be considered and discussed with final users, and basically will include:

- 3D city model visualizations
- data and information integration
- simulations of urban plan regulations
- land use change detection
- monitoring of spatial development.

Considering the planned user groups, their needs and basic analytical features, data themes were identified, together with their sources and needed update cycles (Tab. 3).

**Table 3** Data themes, update cycles and sources for urban planning module of digital city twin

| Data theme | Update cycle | Source |
|---|---|---|
| 3D semantic model, LoD 2.2 | Annual, change detection | LiDAR 2022, UAV surveying |
| 3D photorealistic model | Annual, change detection | UAV surveying |
| Land use | Planning cycle | Land use maps |
| 3D detailed urban plans | Planning cycle | Detailed plans maps |
| Architectural competitions | Competitions cycle | Architectural plans |
| Land parcels | Daily | National register |
| Planned buildings | Daily | National register |
| Urban greenery | Daily | City green cadastre |
| Population distribution | Census / Daily | Census / National register |
| Thematic GIS layers | Daily | City and National SDI |

Special attention should be paid to the 3D model of the city, because it is a prerequisite for most visualizations and analytical features. Periodic updating from national LiDAR surveys is a potential solution, with an alternative approach in change detection from cadastral records and annual updating for selected locations using UAV imagery.

Although real-time data is usually a core part of any digital twin city, none of the smart city sensors have been identified as essential for the urban planning module.

In addition to the topic of real-time data, the main challenges identified at the moment are issues related to urban simulation features, the relationship between the digital twin and the formal urban planning process, and VR/AR visualizations.

## 7 CONCLUSION

The urban planning and monitoring system is a traditional and important user of spatial and non-spatial data, as well as an important initiator and stakeholder in the development of new smart spatial technologies such as the digital city twin.

The topic of digital twins of cities and urban areas is the subject of many researchers around the world. Academic studies of several researches and projects of digital city twins show the complexity of the topic and different approaches in practical implementations in different cities and different users.

One of the conceptual solutions is to organize a digital city twin as a modular system with a common information platform and several thematic modules. Elements of such a concept include maturity level, scope, purpose, structure, input, processing features, and output.

The City of Zagreb is an example of the implementation of GIS and 3D city models in urban planning, with practical projects of general and detailed planning, architectural competitions and interpolations in protected areas. The city administration is working on upgrading the 3D model of the city for the needs of the future digital city twin.

Based on relevant research and local specifics, the concept of a digital city twin was proposed for the needs of urban planning. The main stakeholders of the project are the city departments for GIS, smart city and IT infrastructure. Key users and visualization and analytical features are defined, as well as a list of data topics, update cycles and data sources.

Developing a digital city twin for urban planning is a complex process with several challenges. Issues of updating 3D city models, using real-time data, visualization and simulation features, and the relationship with the formal urban planning process are still topics for academic research and government consideration.

### Acknowledgment

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