DOI: 10.31534/engmod.2023.2.ri.06m
Professional paper
Received: 30.08.22.

Architectural and Urban Spatial Digital Simulations

Stelios Kouzeleas

Department of Interior Architecture, International Hellenic University, Serres, GREECE
e-mail: stelios_kouzeleas@yahoo.fr

SUMMARY

This study concerns digital tools and simulation methods necessary for the description, conception, perception, and analysis of spatial architectural and urban design. The purpose of the study is to categorize, analyse, and describe the influence of digital simulation tools and methods in architectural and urban design. The study analyses techniques, applications, and research in the field of digital simulations of architectural/urban ensembles while also referring to the benefits of their use both at the level of scientific and spatial perception of architectural/urban design.

KEYWORDS: *architectural and urban digital simulations; digital design; spatial simulation; digital simulations benefits; simulation techniques; categorization of urban ensembles' simulations.*

1. INTRODUCTION

The evolution of computers and multimedia with the parallel development of Computer Aided Design (CAD) systems, Geographic Information Systems (GIS), and information technology with high-resolution dynamic mapping [1] opened a new path in simulations of architectural/urban ensembles with digital cartography and the multimedia application with images of numerical retrieved maps [2]. In the mid-1990s the introduction of Virtual Reality (VR) technology with the Virtual Geographic Environment (VGE) allowed dynamic navigation in a spatial digital environment by contributing to the creation of digital cities [3], with complexity, vector data, and raster processing in OpenData context. New technologies such as telecommunications, multimedia and Augmented Reality (AR), urban mapping, and architectural/urban simulation applications create publicly available results based on innovative tools, such as dynamic programming (e.g., eXtensible Markup Language - XML), facilitating the exchange of structured data, document coding, and data serialization with the ability to search and deliberate in real time [4]. However, problems in digital simulations [5], such as the combination of 3D realistic simulation with the management of complex online cartographic databases [6], the need to create free open-source 3D simulation tools [7], and legal or administrative issues of access and recognition of information analysis [8] remain to be resolved in the future.

Modern technologies such as interactive multimedia, digital mapping, remote sensing, VR and AR, spatial digital simulations, etc., are today important components of architectural/urban reconstruction spatial creation and analysis. Many categories of architectural/urban ensemble simulations combine digital spatial simulation and architectural/urban reconstruction proposals such as digital cities. Digital cities, as a category of digital spatial simulations, are at the heart of combining and adapting digital tools to represent spatial ensembles and contribute to architectural/urban reconstruction.

New technologies, such as VR and AR, can create an immersive experience that allows the user to interact with objects, evaluate public architectural/urban space proposals interactively and understandably, involve society, and democratize decision-making in complex architectural / urban projects [9].

3D geo-visualizations of architectural/urbanised areas retrieved from satellite images [10] contribute to the comprehension and analysis of urban areas while combining satellite remote sensing and GIS into a unique system allows the analysis of the geographic space [11]. Finally, multimedia 3D cartographic applications create comprehensive platforms and communicate spatial related information by contributing to the perception of space [12].

This study presents a general categorization of both digital simulations of architectural/urban ensembles and the techniques used to implement them. It also presents indicative examples/applications and relevant research framing this categorization. Finally, it concludes with the benefits of the contribution of digital simulations in architectural/urban design and spatial perception.

2. GENERAL CATEGORIZATION AND EXAMPLES OF URBAN ENSEMBLES' DIGITAL SIMULATIONS

2.1 CRITERIA OF CATEGORIZATION

Types of spatial representations could be a great approach in order to define a general categorization of urban ensembles' digital simulations. Thus, a categorization could be influenced by the geometric type (scale and orientation relationship between reference systems), by the projective type (cylindrical, conical, and flat), or by the cognitive type (a form of semantic representation-schema) [13].

Another qualitative approach, such as the Qualitative Spatial Representation or Reasoning (QSRR) approach, provides a qualitative and relational understanding of space by describing qualitative spatial relations between existing objects (e.g., indispensable for modelling spatial aspects, new knowledge deriving, etc.) [14].

Other categorization approaches are based on distinctive attributes of each representation. Thus, maps involve scaled representations with a reference system, diagrams are abstract and schematic, while pictures bring impression, expression, and realism [15]. The identification of significant attributes of representations could be influenced by static or interactive manipulations [16], while other factors, such as accuracy, abstraction, and realism are also issues of representational content and usability in order to elaborate this categorization [17].

Finally, other works categorize spatial digital simulations according to their data and context nature [18]. This categorization is based first on the '*data format'* with the 'level of abstraction' containing only key information (high level) or more detailed information (low level) and the 'degree of realism' trying to associate representation with real-world situations. Afterward, it is based on the '*data content'* with the '*data domain'* which defines what is representable and how it can be represented. This involves information linking, coding, querying, and retrieving issues across different disciplines. *'Data types'* are also part of the data domain because they include spatial / non-spatial and quantitative/qualitative representations. Finally, the categorization is based on 'context of use' which defines the generalization (early stage of project development) or the clarity and the detailing of information (advanced stage of project development).

In this work, categorization is mainly based on the following set of criteria:

1. the nature of digital representations and the methods/techniques by which they are approached (e.g., 3D city, Sprawl, multimedia, VR, etc.);
2. the distinctive attributes (e.g., scale, cartography, etc.) as well as the purposes of the representations (infrastructure, marketing, etc.);
3. the phenomena that the representations occur (e.g., interactivity, immersion, information intensity, etc.).

For optimization reasons, one or many of the above criteria of the same set is applied to the digital simulation's categorization according to the nature of the digital simulation. Thus, it is preferred that "digital cities" be a category by itself even though in reality digital cities are related to "Virtual 3D city modeling", and this is because the main criterion/characteristic of their categorization is the existence of a database in relation with distinctive attributes such as scale, thematic cartography, graphic data, and virtual scenarios estimation. Then, the distinct categorization of "Virtual 3D city modelling" is based on a very wide range of engineering and non-engineering purposes (e.g., design, infrastructure, marketing, learning, etc.) because this criterion influences and involves the main techniques used in this category. The methods/techniques (e.g., multiscale geography, GIS, spatio-maps, etc.) are the main criteria that generate "3D dynamic simulation and sprawl modeling", while phenomena that characterize digital representations remain the main categorization criteria of "multimedia simulation" category (e.g., immersion, information intensity, etc.) and "VR / AR" category (e.g., interactive view, spatial integration, virtual superimposition, etc.).

Consequently, the main five general categorizations of 'digital cities', 'Virtual 3D city modeling', '3D dynamic simulation for urban sprawl modeling', '3D multimedia spatial simulations', and 'VR and AR' and their respective examples of urban ensembles' digital simulations are presented below.

2.2 DIGITAL CITIES

Many scientific terms are used to describe digital cities, including the virtual city related to systems and methodologies of digital design and simulation [19], the city of information [20], the invisible city [21], the smart city, etc.

There are three main categories of digital cities on the Internet:

1. "Mirror cities" that use, inter alia, all possible digital simulations (photographs, panoramas, rendering, maps, animation, etc.) providing realism and great accuracy [22];
2. "Tool cities" that use interactive applications to transfer city functions to the numerical space, offering a range of services [23];
3. "Portals cities" that use portal pages with online guides and information for mainly advertising purposes [24] (Figure 1).

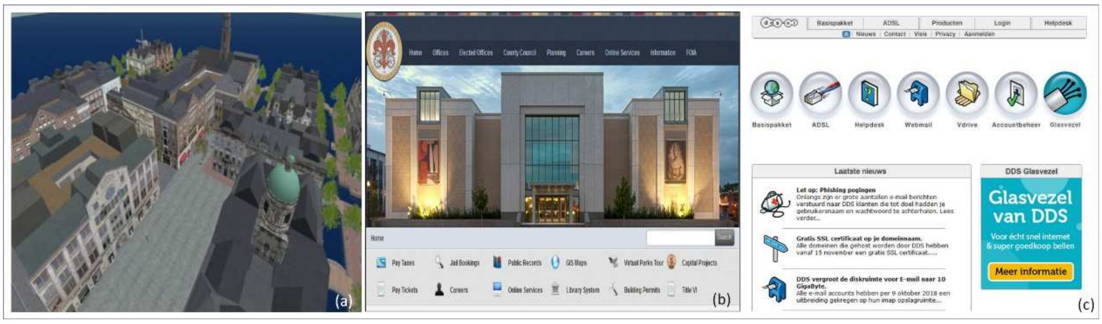

Fig. 1 *Examples of digital city classification: a) Mirror City - Amsterdam [25]; b) Tool City - Florence, [26]; c) Portal City - Amsterdam, [27]*

The types of digital simulations of architectural/urban ensembles based on the creation of digital cities on the Internet are categorized in relation to:

1. simulation with databases that provide data for further spatial and qualitative analysis;
2. simulation without databases that represent the space for mainly touristic purposes and service functions [28].

Therefore, digital simulations of architectural/urban ensembles differ and are categorized according to the existence of a database, their scale, and their nature [28] (Figure 2):

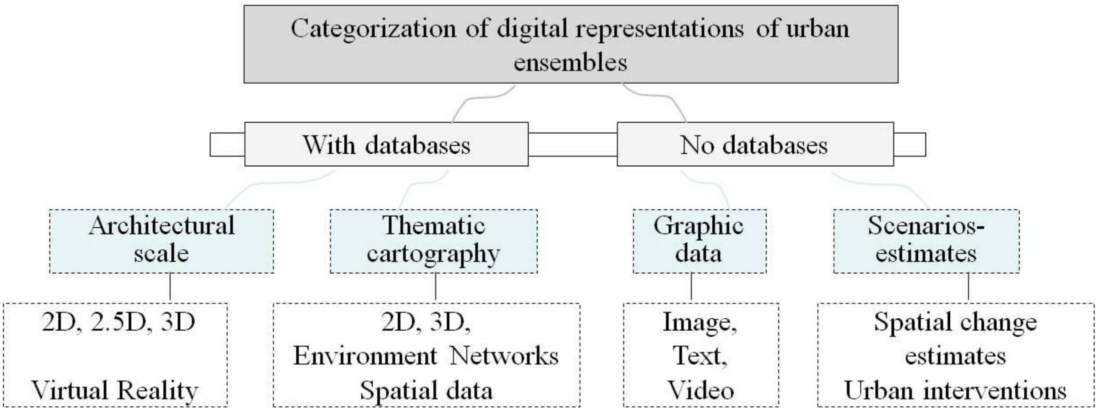

Fig. 2 *Categorization of digital simulations of urban ensembles*

1. *Architectural scale* (diversity of simulations in relation to the level of visual detail using all three levels (2D, 2.5D, 3D). A typical example of 2D digital simulation with databases is the digital urban complex of Prague with multiple possibilities, such as creation and editing of maps, hybrid navigation with Google map technology, use of programming (JavaScript, XML), and exchange of data through "Really Simple Syndication" method (RSS) [12]. A typical example of a 2.5D digital simulation of an architectural/urban ensemble without a database is the city of Tallinn in Estonia, created using virtual navigation in multimedia platforms and programming (ActionScript, JavaScript) [28]. A typical example of a 3D digital simulation of an architectural/urban ensemble with photorealistic models and databases for spatial analysis is the USA city of Philadelphia [29], and Berlin is a typical example of a digital city without databases with photorealistic navigation based on photogrammetry solutions and high-resolution satellite images for mainly touristic purposes [30] (Figure 3).

Fig. 3 *a) Hybrid 2D map of Prague with autofocus function [31]; b) Interactive 2.5D virtual tour map of the historic centre of Tallinn [32]; c) 3D digital simulation of Philadelphia USA [29]*

2. *Thematic cartography* (simulations of physical, cultural, social, economic, political, sociological, and other aspects of urban ensembles). A typical example of 3D thematic cartography without databases is Genoa's architectural/urban ensemble, which allows a participative design with available data such as GIS, environment, energy, and territorial information [33] (Figure 4).

Fig. 4 *Example of thematic cartography, Genoa [33]*

3. *Graphic data* (attractive and easy access to spatial and descriptive information with a minimalist graphic design of the most important points of interest to avoid confusion and to strengthen the spatial perception through graphic approach cartography of the architectural/urban ensemble with multimedia highlighting of the selected spatial). A typical example of a comprehensible and ergonomic simulation is the city of Canberra [34], which contributes to the general perception of the space, thus making it suitable for deliberation with the public (Figure 5).

Fig. 5 *Graphic multimedia digital simulation - Canberra, Australia [34]*

4. Scenario-estimation simulations based on future proposals (related to data in a digital space simulating future intervention in the architectural/urban network or possible scenarios and the impact of their implementation). A typical example without databases is the study of the Stuttgart urban ensemble known as VEPs (Virtual Environmental Planning Project) [35], which combines 2D and 3D simulations of quantitative and qualitative data (environmental models, noise, floods, etc.) with digital tools for users' participation in design decisions (Figure 6).

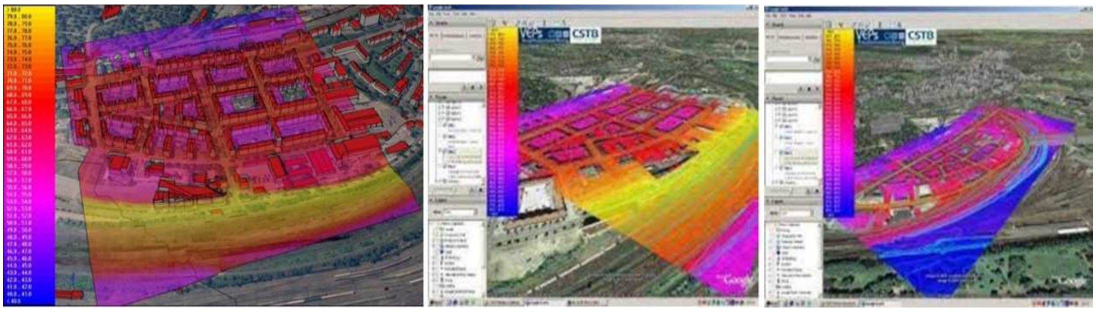

Fig. 6 *Digital simulation of scenarios-estimates of the architectural/urban ensembles of Stuttgart [35]*

2.3 VIRTUAL 3D CITY MODELLING

3D City models can be created for a very wide range of engineering and non-engineering purposes, which have been enhanced and grouped into four main categories [36]:

1. Design and Planning;
2. Facility and Infrastructure services;
3. Marketing and Commercial sector;
4. Learning of information and Promotion of cities.

Various advanced algorithms are used by many applications to create accurate 3D city models. The accuracy of the 3D City model depends not only on the Level of Details (LoDs) but also on the scale of aerial/terrestrial images taken. The main applications of virtual 3D City models consist, inter alia, of e-governance, environmental planning and analysis, navigation, tourism, etc. [37].

A typical example of using the 'CityGML' standard with BIM software allowing photorealistic texturing with ETL CAD transformation (Extract, Transform, Load) and data analysis is the 3D model of the Faculty of Philosophy and Law of the University of Novi Sad [38]. Other typical examples of 3D city models via automatic modelling software generate geometries and terrain based on laser data, aerial images, and 2D digital maps [39] (Figure 7).

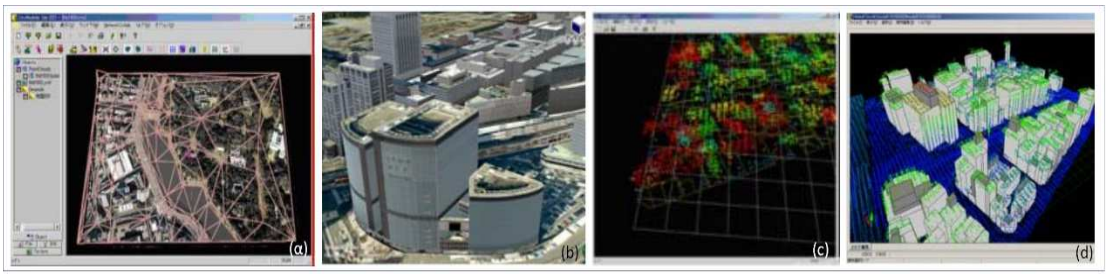

Fig. 7 *a) Terrain modelling tool; b) MapCube; c) Building model generation tool; d) Building model edition tool*

2.4 3D DYNAMIC SIMULATION FOR URBAN SPRAWL MODELLING

Some principal elements of 3D dynamic GIS are 3D simulations, dynamic procedure, and time which allow the production of urban sprawl geographic knowledge with MGD (Multiscale Geographic Dimension), in other words, scales and images of cartography representations [40]. MGD contributes to visualizing, modelling, and analysing urbanization processes from the local to the global levels.

Planning and land use management are significantly assisted by monitoring urbanization procedures since they are useful in highlighting conflict areas generated by the urbanization of farmland [40], creating epidemiological impacts on populations [41], or preparing environmental standards to be applied [42].

In any case, there are various limits in 3D dynamic representations among which are the geographic databases management and their quantity and quality [40]. A typical example of the use of the 3D dynamic GIS is drawn out from the synergy of various GIS elements, such as time, 3D dynamic representations, with spatio-maps of urbanized areas, image processing operations based on geomatic and satellite data, as the typical example of Aravalli Mountain barrier (Jaipur) (Figure 8).

Fig. 8 *The Aravalli Mountain barrier (Jaipur). STRM WR-2 DTM merged with a colour composite generated from Kompsat-2 images of 16 December 2006 [40]*

2.5 3D MULTIMEDIA SPATIAL SIMULATIONS

Modern spatial cartographical presentations provide modern communication methods for spatially related information [43]. Thus, the use of multimedia tools creates an effective additional aspect to the cartographic communication process [44]. Geo-visualization that uses 3D multimedia cartography seems to provide real support for knowledge acquisition [12].

Graphical components in 3D multimedia CIS (Cartographic Information Systems) or applications and computer graphics are the essentials that consist of various elements, such as complex models, textures, lights, camera management, etc. [12].

The basic factors in creating a 3D multimedia spatial presentation [45] are:

1. Immersion (the user's submersion in a virtual cartographic environment),
2. Interactivity (contribute users to orientate and extract information),
3. Information intensity (formalize and quantify the LODs),
4. Intelligence of objects (supporting users to interpret a cartographic environment), [46].

A typical example of 3D multimedia spatial simulation use is a fully 3D Object-Oriented System called DILAS. This system is a 3D geo object data management model with many levels of high-resolution terrain and texture data such as ortho images, raster maps, DTM, animation models, etc. [12], [47], as shown in Figure 9.

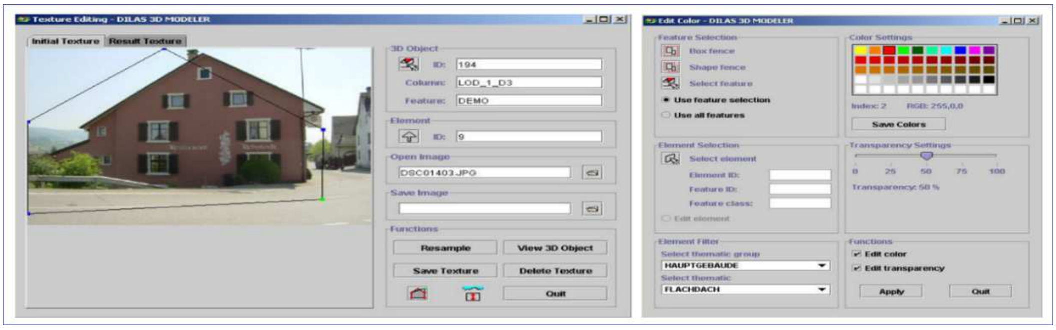

Fig. 9 *DILAS 3D Modeller – Texture & Semantic Colour Editor [12]*

2.6 VR AND AR

Augmented reality (AR) is the extension of Virtual Reality (VR) (interactive view and movement in a 3D virtual environment) and is defined in its turn as the extension of a user's perception with virtual information combining real and virtual elements in real-time. The spatial information can be directly displayed in real-time, and the interaction can take place in a simple and intuitive way [48].

Mixed Reality (MR) is characterized by its spatial integration with the environment of the real world and the visual realism of the non-real world. This spatial integration concerns the superimposition of 3D/rendered virtual objects with real-world environment objects by transforming these objects into augmented objects. Thus, various maps are created and integrated into geospatial Web services with online access [49].

A typical example of AR spatial simulation is ARTopos [50], a prototype tabletop AR application that uses a paper topographic map as a marker that combines the orientation and the scale of the map across devices. The DTM (Digital Terrain Model) used for augmentation is a realistic simulation of the world with its corresponding WGS84 spatial reference system that uses a simple ray-casting algorithm to convert 3D models into latitude and longitude coordinates (Figure 10).

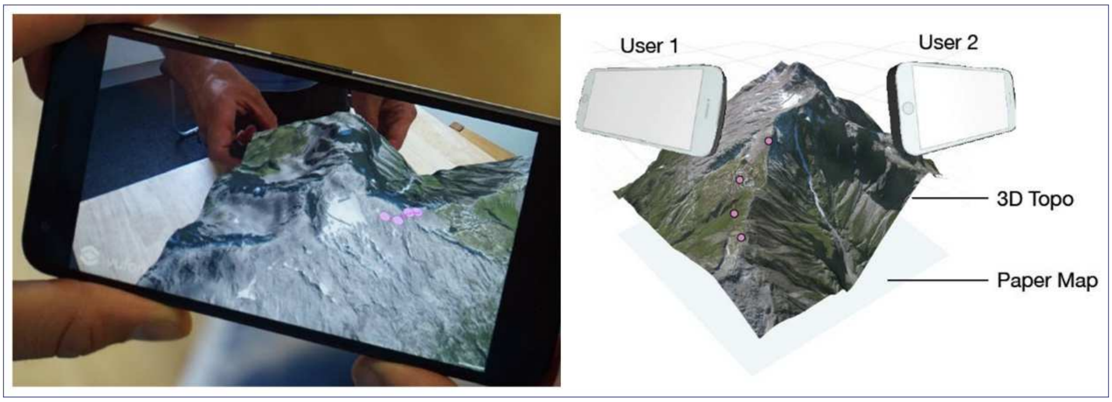

Fig. 10 *ARTopos: A prototype tabletop augmented reality application of topographic spatial simulation [50]*

3. ARCHITECTURAL/URBAN DIGITAL SPATIAL SIMULATION TECHNIQUES

A clean separation of digital simulation from methods/techniques has been made to optimize both the definition/description of the categories and as well as the large number and complexity of different techniques used. This choice allows the 'multi-disciplinarity' relation between category and technique, in other words, the involvement of each technique in one or many categories and vice-versa, that is, each category contains many different 'multi-nature' techniques.

Several techniques are applied in architectural/urban digital spatial simulations, from 3D city modelling to urban sprawl modelling 3D multimedia spatial simulations, and VR / AR. These techniques are both conventional, such as vector map data, DEM, aerial images, LASER high-resolution satellite images, photogrammetry, and texture mapping, and non-conventional, such as video, and AR.

3D models of large cities are produced in real-time by a combination of techniques, such as photo textured on web applications, a combination of aerial and terrestrial laser with photographs, and automatic geomatics methods based on photogrammetry/laser data, or 3D city model creation of specific software [37].

Geomatics techniques play a major role in creating a virtual 3D City model. Each technique has some advantages and disadvantages. Some main architectural/urban digital spatial simulation techniques relating to 3D virtual city modelling are [37]:

1. GIS and aerial photogrammetry: The photogrammetry method contributes to an object attributes' automatic extraction. On one hand, this method uses traditional photos taken from the ground with the advantage of low cost but the disadvantages of lack of private backside buildings photos, managing several image files, and fixing textures. On the other hand, it uses aerial satellite images with the advantage of using a few images and fixing building textures being extracted from the same image, but with the disadvantage of the high

cost of aerial photos [51]. Many 3D City model applications have been developed using GIS and photogrammetry techniques [53], [37], while other applications, such as CyberCity modeller, have been developed for automatic 3D point cloud topology generation [53].

2. Aerial Photogrammetry-based model: A semi-automatic method for acquiring 3D topologically structured data from 2D aerial stereo images [54].
3. Satellite Photogrammetry: Developed and tested a methodology for semi-automatic city model extraction from tri-stereoscopic very high-resolution satellite imagery [55].
4. Panorama Photogrammetry: Studies give a methodology for Piecewise Planar City 3D Modelling from Street View Panoramic Sequences [56].
5. Single Satellite Image: An application proposes a method for object reconstruction from a single high-resolution satellite image using the Monoplotting technique [57].
6. Computer Vision Techniques: A technique describing a semi-automatic system for acquiring the 3D shape of buildings as topographic objects [58].
7. Aerial Images and Cadastral Map: A technique creating a building reconstruction framework for 3D city model production using aerial images and cadastral maps [59].
8. Video: Videogrammetry is a measurement technique mainly based on the principles of Photogrammetry [60].
9. LASER: Studies investigate and propose a methodology and algorithms for automatic Generation of Three-Dimensional Photo-Realistic Models from Lidar and Image Data [61].
10. Web-based: Studies evaluated the concept of OpenStreetMap (OSM)-3D [62]. Other studies investigate the generation of interactive 3D City Models based on free geo-data available from the OpenStreetMap (OSM) project and height information provided by the Shuttle Radar Topography Mission [63] (Figure 11).

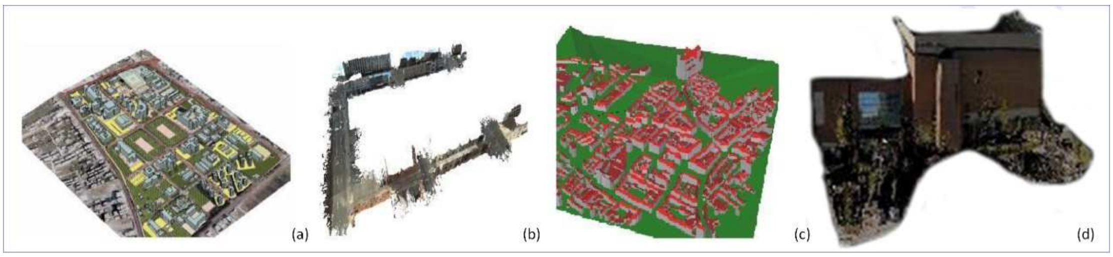

Fig. 11 *a) 3-D Model for Yarmouk University (Al-Hanbali et al., 2006); b) City model reconstruction from car image sequences [56]; c) 3D City model [59]; d) Textured point cloud model with laser and Images [61]*

The main 3D urban sprawl modelling techniques are related to almost all 3D virtual city modelling techniques and particularly/additionally concern:

1. 3D dynamic spatio-temporal Geographic Information Systems (GIS): They are created from satellite images, maps, and geo-referenced databases and contribute to the analysis of the urbanization and aerosolization processes [40].
2. Digital Terrain Models (DTM): DTM is a 3D spatial simulation of a geographical portion representing altitude values in a matrix of pixels or dots [64]. It is a combination of a 3D dynamic model and simulation, which analyses urban transformation processes and allows a better geographic perception [40].

3. Remote sensing: Techniques that allow detection, quantification, and qualifying urban land use changes by completing in this way the decision-making process [65]. These techniques also allow the assessment of land use changes compared to socio-economic indicators such as population growth, urban sprawl, real-time acquisition, and multi-spectral characteristics [66], [67]. Since remote sensing alone can't fully describe urban sprawl and change, there is a need to incorporate landscape and spatial numerical indices [68], [69], [70], to quantitatively measure and fully describe the underlying spatio-temporal structures and patterns in any landscape [71], [72], [69].

A 3D multimedia presentation combines tactile, visual, and aural components in a computer-based, multi-modal/coding, and interactive environment [12]. 3D multimedia Cartographic Information Systems combine many technical requirements, such as programming, GIS, photogrammetry and remote techniques, formats/quality/description of data, etc. [12].

The main 3D multimedia spatial simulation techniques are related to many already cited techniques and particularly / additionally concern:

1. Stereoscopy: Techniques such as multi-stereoscopy and the pulfrich effect, are used in 3D multimedia spatial simulations by integrating visual presentation forms, such as P3D - "Parallax 3D" which employs specific depth cues [12].
2. Holography: All directions effects of parallax producing volumetric imaging, light-emitting volume, and rotating helix mirror processes [73].
3. Coding/programming structure: Applications of spatial multimedia photogrammetric and cartographic simulations that use common formats, such as VRM and XML. The storage format of these 3D objects is a JAVA and XML database providing modelling flexibility, object query, and retrieval performance.
4. System architecture/applications: Different 'architecture systems' based on 3D geo-objects or 3D object data-management models, object-oriented, etc. [47], photogrammetrically recorded objects, generalization models [74], GIS functionalities, photogrammetry, etc. embody the competence of various details as well as texture and visualization information, such as raster maps, ortho-imagery, terrain, and surface models.

The main VR, AR, and MR techniques are related to:

1. AR modelling techniques: These techniques use data of 3D models exported either from Geo-DataBase Management Systems (GeoDBMS) or from geospatial databases in GML standard (Geography Markup Language) [75]. These techniques allow, inter alia, 3D model visualization in real-time, control of data access, and data management of a geospatial database [76].
2. Visualization techniques: Depth-cues techniques (occlusion, shading, shadows, parallax) [77], artificial meta-objects illustration techniques, and visual abstraction techniques [78] use many AR display techniques, such as video-see-through-display, optical-see-through-display, and projection-AR-display.
3. Interaction techniques: Established Graphical User Interfaces (GUIs) is a common technique based on the WIMP concept (windows, icons, menu, pointer) applied in MR applications [79]. Tangible User Interfaces (TUIs) is a technique that uses physical objects as simulations and controls for digital information and application control [80]. User

gesture recognition techniques use camera-equipped mobile devices, such as smartphones and PDAs.

4. Web services: Services for the online delivery of geospatial data, such as Web Map Service (2D maps) [81], Web Feature Service [82], and Web Coverage Service [83] (geospatial vector and raster data), with an online data analysis or creation of new information [84].

4. BENEFITS OF ARCHITECTURAL/URBAN SPATIAL DIGITAL SIMULATIONS AND RELATIONS WITH METHODS/TECHNIQUES

4.1 BENEFITS

Digital spatial simulations become a tool to help the process of spatial design, conception, and perception. Nevertheless, it is necessary:

1. to adapt these tools to the conception process which depends, inter alia, on the simulation goal, and the way they impact users to interpret spatial connexions,
2. for the conception process and the spatial design to be critically adapted to the use of these tools [28].

In many cases, spatial digital simulations enable users to participate in the planning and deliberation of spatial proposals and possible interventions as they allow the simplification of information in an explanatory way. This allows the integration of a “participatory design” into the whole conception process, considering the opinion of non-experts and contributing to the creation of a common language of communication between experts and the public in architectural, urban, urban planning or even Participatory Guarantee System (PGS) projects [28].

Spatial digital simulations often allow users to participate in “participatory design” and deliberation of future proposals as they not only allow a better understanding of the information throughout the conception process but also create a common language of communication between experts and the general public in issues related to both spatial design and the formation of a Participatory Guarantee System (PGS) [85].

Spatial digital simulations highlight space and its corresponding geographical references in a more complete way, allowing correct spatial analysis, correlation, and understanding of complex scientific information. The simulation of spatial characteristics allows both the study and perception of space as it becomes a tool for analytical information. At the same time, these tools enhance the participatory nature of spatial design, enabling a holistic spatial approach by contributing to the decision-making of future interventions and the management of their consequences [28].

3D spatial simulations with the corresponding navigation, orientation, and other cartographic variables are perceived as advantageous [86]. The benefits of these simulations for architectural/urban design contribute, inter alia, to the familiarisation of context, and the modelling improvement, as well as to a better assessment of effects [87].

Web-GIS map simulations present many benefits related to the integration of spatial data from various sources and to a better understanding of space and opinions management for participants in participative design [88].

AR and VR visualization systems present many benefits related to the (a) contribution of decision-making procedures, (b) enhancement of spatial perception, (c) involvement of participants in decision-making impacts [49], (d) manipulation of real-life objects and (d) enhancement of visual perception by using immersion sensation.

E-participation services in architectural/urban projects present various benefits related to:

(a) enhancement of decision-making operations;
(b) facilitation of idea exchange between experts and citizens;
(c) enhancement of citizens' proposals for potential simulation.

3D spatial representations and virtual models answer architectural design requirements by controlling the multithreaded complex building structure and sharing information with other stakeholders of the conception process [105].

4.2 RELATIONS OF DIGITAL SIMULATIONS WITH METHODS/TECHNIQUES

Digital spatial representations of architectural and urban planning are defined and influenced by the methods and techniques represented. This creates a direct relationship that, according to many researchers, affects both their categorization and their further analysis. The complexity of these digital spatial representations raises many conflicts because they cannot be presented by any single means of representation, and this may cover one agenda while not satisfying the others. Thus, spatial representations cannot be separated from associated agenda, and discipline/ individual preferences [106]. For example, what would be the appropriate way to represent an area of architectural scale? A 3D CAD design approach, a Virtual Reality design approach, a Virtual Tour design approach, or even a GIS mapping approach?

Today, most computer support design and representation systems are used in isolation from other related disciplines, while some other support systems implement design collaboration between discipline/ individual preferences with many limitations [107].

To allow the bi-directional and multiple use of different methods of representation, there is a need to systematically determine the usability and definition for potential information loss in each method and technique representation engagement. For example, a prototype system (REX) has been developed to support design decision-making in collaborative design by implementing details and preliminary evaluation of representation software using different methods and techniques and identifying the limits in computing the translation between these multiple representations [18].

Facilitating multiple representations in a project results in two advantages: inferences with other design disciplines, and inferences within each discipline [18].

Other methods evaluate the performance of spatial simulation models through analysis and comparison of spatial patterns (in which they decompose and simulate space) [108].

5. DISCUSSIONS AND CONTRIBUTIONS TO SPATIAL DESIGN, CONCEPTION, AND PERCEPTION

Scientific knowledge management is dominated by research that is based largely on the visual approach and not on the textual one [89]. Visual simulations and compositions are considered the starting point of a conception process [89]. Visual simulations can be considered a key component of both architectural thinking and design methodology as they can combine traditional architectural and purely scientific approaches in a detailed way [90]. Today, modern tools and methods are combined to create new scenario simulation tools for sustainable cities [91]. Scientific engineers can give existence, form, and methodology to adopt modern media in an appropriate way [92].

Digital spatial simulations compose multi-spatial/sensory approaches, allowing a holistic approach and perception of space. The multifaceted modes of simulation enable the emergence of architectural/urban components influencing the conception process and the design result itself [93]. Thus, these simulations contribute to spatial perception since they allow a more complete spatial design and a detailed analysis of spatial components.

Perception is defined as the way of using memory to sense what is happening and to calculate the motor responses required to negotiate objects in space [94].

The three factors contributing to the perception are:

1. motivation (an internal factor that causes human behaviour),
2. memory (the imprint of what happened; perception is related to memory because humans understand more easily events related to past experiences),
3. learning (internal simulation of external reality) [94], [95].

The process of spatial conception and analysis is complex as it is interdisciplinary with different types of information that need to be synthesized understandably. Since the processing and the required correlation of all spatial information is not easily feasible and practical, the simulation of architectural and urban space is more than necessary. Digital architectural/urban simulations allow this correlation that emphasizes the spatial dimension. Thus, it is possible to extract valuable results by creating a holistic picture of the space and its future spatial proposals. In particular, the parallel simulation of quantitative and qualitative data on a digital map is a typical example of spatial simulation and analysis. Digital architectural/urban simulations are important information tools and not just support, enabling a holistic simulation and spatial data analysis, enhancing the participatory nature of design, and contributing to an integrated spatial approach to physical and virtual space simulation [28].

During the process of design conception, spatial digital simulations (a) help engineers to better understand space by reducing design constraints, and (b) contribute to identifying causes of problems, categorizing, and linking them to spatial entities by enabling engineers to predict and control events. Digital scale architectural simulations allow spatial simulation with precision and interaction with space by providing additional information and functions, such as location, advertising, promotion, etc. They also allow access to hybrid cartographic data by simulating maps with satellite, urban, and architectural spatial data with scale change and analysis of spatial elements, contributing to spatial perception without necessarily the corresponding spatial detail. The use of such simulation tools requires a prior adjustment to be effective in the design process. This adaptation depends on:

1. aim of the simulation,
2. spatial entities to highlight,
3. way to use these digital tools,
4. ability of the user to make spatial relationships, etc.

However, the design conception process itself needs critical thinking and adaptation to the use of these tools, even if the engineer must protect the conception process from the requirements of digital tools [28].

Architectural/urban digital spatial simulations allow environmental assessments and focus on specific urban components by contributing to the spatial interpretation and the conception process. The digital simulations of design projects contribute to different types of analyses based on experiential data. Representation tools facilitate both public deliberation and decision-making as well as the understanding and management of quantitative, qualitative, and temporal peculiarities of architectural/urban space that are not manageable with traditional tools [93].

The relationship between the physical and virtual spatial worlds contributes to and influences the design and construction process as well as the corresponding role of objects. Models in an AR environment improve communication during the design process by supporting a better understanding of the design project results [93]. Architectural/urban digital simulation tools improve organizing and integrating public opinion into design proposals and enhance "participatory design" by contributing to better communication between the expert scientist and the citizen [28].

Consequently, the contribution of architectural/urban digital spatial simulations to the spatial design process and perception is obvious and practical. These simulations are used in different forms, such as programming, decision-making, and planning/space analysis tools. The advantages can lead to a reduction of compatibility problems in terms of spatial reasoning approach and a more realistic, innovative, and functional interface with ever-changing technologies, complementing and multiplying the abilities and thoughts of designers and users.

6. RESEARCH AND PERSPECTIVES

Digital simulation research of architectural/urban ensembles is diverse and interdisciplinary. Key relevant research pillars based on various corresponding interdisciplinary fields are related to:

1. Automatic modelling (Figure 12): 3D simulation of architectural/urban models and automatic digital design and simulation via VHF wireless devices [90], automation of modelling based on spatial photographs, aerial photographs, and georeferenced images [5], either through accurate photogrammetric methods [97] or with special applications based on algorithms that generate photorealistic images [98].

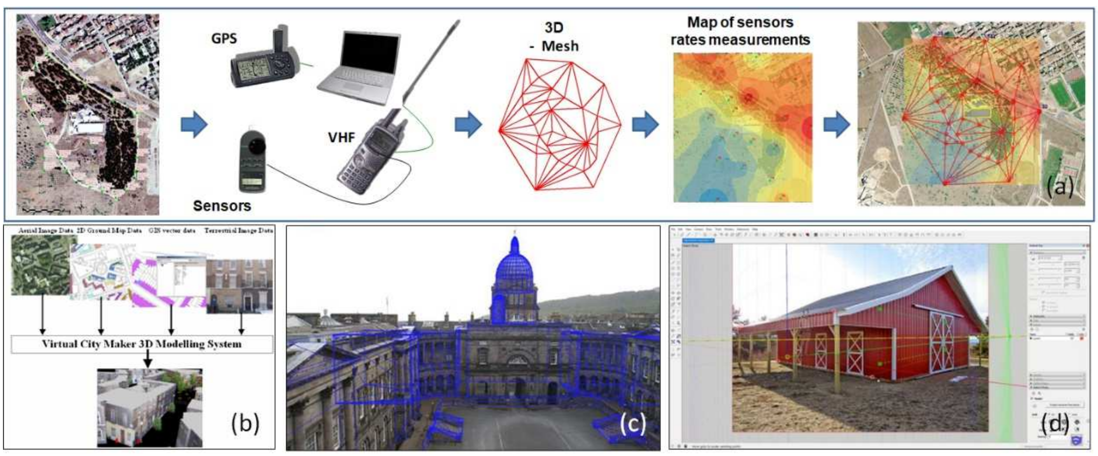

Fig. 12 *Examples of automatic modelling: a) Automated remote modelling process [96]; b) Photo-based, "virtual city maker" [98]; c) Photo-based capture [99]; d) Based on photos [100]*

2. Mobile simulation: export of 3D interactive architectural/urban environment to mobile devices (mobile phones, tablets, watches, GPS, etc.) where the interactive virtual tour and AR environment dominates (Figure 13).

Fig. 13 *Examples of mobile simulation: a) Augmented Reality [101]; b) Virtual Reality [102], c), d) Design of an original mobile virtual navigation interface [98]*

3. Automatic spatial data capturing: automatic spatial applications either with special devices and photogrammetry methods (laser 3D scanner) [102] or with adapted software on devices (Figure 14).

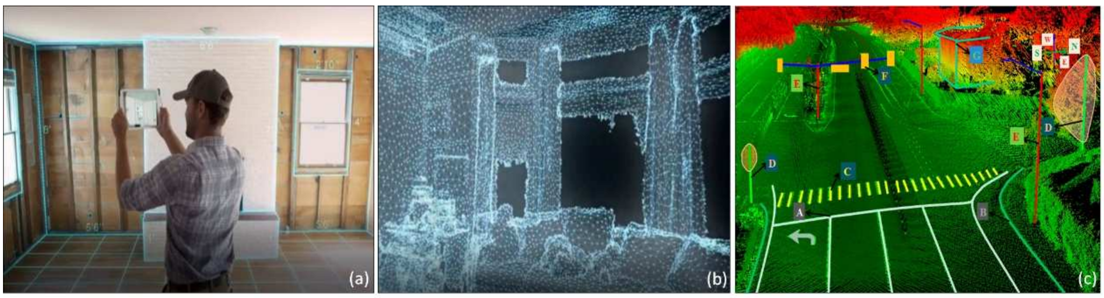

Fig. 14 *Automatic spatial data capturing applications: a) Applications of special devices [103]; b), c) Application of 3D laser scanning [102]*

The perspectives for digital simulations of architectural/urban ensembles are directly related to both evolving technology and the need to adapt this technology to scientific, social, economic, health, and other human needs. Some of the modern evolving technologies that will directly affect digital simulations are:

1. satellite telecommunications (remote design and interactive applications);
2. Internet and data transfer speeds (real-time applications, mobile applications);
3. VR and AR (synchronized simulation of real and virtual world);
4. sensors and use of measurements (adaptation of measurement values from sensors to digital simulations of virtual spaces, combined overlapping information with spatial reference and holistic approach to space analysis, digital and smart cities).

7. CONCLUSIONS

Digital simulations contribute to social inclusion as they allow the additional evaluation and appropriation of architectural/urban space while additionally improving the user's interaction with space and objects [9] and optimizing the perception of modelled space while minimizing spatial ambiguity [104].

The contribution of digital simulations both to architectural, urban, and spatial planning and to spatial perception is enormous, through either the projection of issues or analyses of spatial units or participation in design issues, in particular:

1. tourism promotion and development through integrated and realistic digital simulations, strengthening of spatial perception, identification of locations, routes, addresses, services, social and business processes;
2. access and collection of information by finding areas of architectural/urban surfaces, vectorial distances, and altitudes for further corrections, changes, and analyses in multiple applications such as commercial, educational, social, market research, business cooperation, and contact, etc.;
3. participatory design that creates conditions for the solution of problems related to the formation of views/thoughts, deliberations, and decision-making by managers and citizens on issues of spatial proposals and interventions;
4. scientific analysis enabling the identification of problematic spatial units, identifying the causes, assisting in the spatial identification and analysis of “disturbing” areas, and contributing to the ability to predict, control, and influence design decisions in future studies of architectural, urban, environmental, social, economic and energy interest.

The digital simulations of architectural/urban ensembles, in short, are used:

1. to create a common language of communication between scientists and citizens,
2. as a tool for planning and understanding complex development factors,
3. as a decision-making tool (location of activities, land use, environmental data management, etc.) and
4. as a spatial design and planning tool.

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