Optimising a Virtual 3D City Model for Citizen-Based Urban Development in East Jerusalem

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Abstract. This contribution presents the use of a newly developed approach for the generation and modelling of spatially referenced, multidimensional virtual city models from remote sensing data, exemplified by the case of East Jerusalem. The focus is on the effective application of the entire process from data acquisition, pre-processing and management to spatial analysis and applications. Using East Jerusalem as a study area, the contribution demonstrates how high-resolution stereo aerial imagery and semantic data from various sources can be integrated to form a fully referenced virtual multidimensional spatial model. The resulting digital city model offers user-specific functions for spatial exploration. It thus facilitates a range of applications in the context of urban planning, community development, decision-making as well as, e.g., education or tourism. The work presented shows that a common database must be established, consolidated, and maintained prior to the appropriate use of these models. The modular design of interchangeable components for individual functionalities, workflow segments and applications, along with effective presentation capabilities, are crucial factors to provide ease of use for the user as well as straightforward communication. Practical use cases of the approach discussed are the integration of data on health and education infrastructure, wastewater, and waste management, as well as transport infrastructure and usage, coupled with socio-demographic and socio-economic indicators. These cases demonstrate the scope and, at the same time, hint at the built-in generic capabilities allowing to transfer the methodology to different fields of applications. In summary, the approach presented here allows for the generation of diverse virtual city models which in many regional and thematic contexts constitute an appropriate starting point for sustainable and efficient urban development. It can be shown that the range of use cases can easily be extended to accommodate for new applications and different regional settings. The presentation highlights some methodical, technological, and content limitations that had to be overcome to adequately build, visualise and utilise 3D virtual city models to help foster sustainable and efficient urban development.

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1 Overview and Context

This contribution discusses the application of a newly developed process for the generation and modelling of spatially referenced, multi-dimensional virtual city models from remote sensing data for the urban area of East Jerusalem. This approach has been developed and applied within the framework of an EU R&D project (ENI/2018/397-546). The overall objective of this project was to strengthen the political, economic, and environmental participation and self-determination of the city's Palestinian communities and organisations. One important aspect of the project was the creation of a comprehensive database on East Jerusalem for civil society, including local communities, national/international state and non-state actors and Palestinian businesses. In this project, a specially developed generic workflow has been used to cover the entire process chain from data collection to appropriate visualisation in order to communicate information effectively. The preparatory work is described in detail in [6–8]. Using this generic workflow, the project has set up a comprehensive geodatabase through the acquisition and processing of high-resolution stereoscopic remote sensing imagery. The geodatabase contains up-to-date 3D geospatial and thematic data of unprecedented scope and depth, allowing for detailed analysis of the social, economic and environmental conditions of East Jerusalem communities. To facilitate the use and dissemination of this data, the ALQUDS.INFO digital platform has been developed and made available. This platform is used for decision-making, education, and research by civil society, community stakeholders and the general public.

2 Problem Statement and Challenges

Creating meaningful and accurate 3D city models for urban planning and decision-making is a challenging task, especially in regions with limited or no reference data at all [1,5]. East Jerusalem is a paradigmatic example of such a case, as it lacks an adequate database for a variety of reasons. The area of East Jerusalem is therefore a suitable study area to analyse the problem resulting from a lack of reference data. East Jerusalem is a complex and historically significant urban agglomeration with political and cultural tensions. Due to the Israeli-Palestinian conflict, information and data on the entire city is often difficult to access or non-existent. This is particularly true for geospatial data, which is essential for the creation of 3D city models. The limited availability of basic geo-topographic data, topographic maps and detailed urban information makes it difficult to develop accurate and comprehensive 3D city models. A special feature of the highly nested structure of the oriental city type is not only a visual

but also a technical challenge of distinguishing objects in the complex urban fabric, as shown in Fig. 1. This situation results in a lack of reference data required for accurate modelling and visualisation of East Jerusalem.



Fig. 1. Representation of the oriental city type with highly nested urban structures. The nadir image creates a visual effect similar to an aerial photograph, but is a highly accurate model that allows detailed representation of building complexes and structures.

Given these challenges, it is important to develop a comprehensive workflow that is specifically adapted to the characteristics and constraints of East Jerusalem. This workflow is to enable the collection of data from different sources, the integration of existing information and the processing of the data into a coherent and accurate 3D city model. Developing such an effective workflow for East Jerusalem has far-reaching implications for urban planning and decision-making. It allows for an improved data base to make informed decisions and promote citizen participation. It can also serve as a model for other regions where lack of reference data is also a major challenge.

3D virtual city models in general are important tools for urban planning and development, as they allow an accurate representation of urban structures and characteristics [13]. To build them, one is frequently faced with the problem of limited or non-existent data, making it difficult to implement urban planning policies and decisions [15]. This is particularly true in conflict areas, such as East Jerusalem, where political conflicts may limit or restrict access to data sources [13]. As a prerequisite for the creation of an up-to-date 3D city model

geospatial data were acquired by a flight campaign capturing high resolution stereo imagery. The mass of geodata was then processed with photogrammetric methods including image analysis, geometric object definition and semantic enrichment through supplementary household survey data.

This contribution focuses on both workflow and optimisation of the existing 3D model of East Jerusalem, in order to make it more useful for citizen participation and urban planning activities. The optimisation of the 3D model must take into account not only the technical aspects, but also the ease of use. One challenge in optimising the 3D model is to improve its efficiency and its usability. In addition, easy communication of information plays a crucial role. Citizen participation is an important factor in the success of urban development processes and should be considered when optimising the 3D model for East Jerusalem. Citizen participation leads to better acceptance of urban planning measures, thus increasing the overall chances of success [2,17]. Another important factor in the creation of 3D virtual city models is the integration of data from different sources. There are a variety of data sources that can be used to create 3D city models, such as remote sensing data, especially LiDAR data, geodatabases, and crowdsourcing platforms such as Open Street Map [10,11,19]. However, these data need to be consolidated, harmonised and provided in a uniform way to create a complete and consistent 3D model [13]. Another issue in the creation of 3D virtual city models is the complexity of the underlying technologies. The creation of 3D models requires some expertise in geoinformatics, computer graphics, geometry and statistics. Hence it is important that experts from different disciplines work together to create and optimise 3D models [11,19].

3 Process Implementation

The creation of such a 3D virtual city model requires a functional process of data acquisition, processing and integration to achieve a detailed and accurate representation of the urban environment. The development and implementation has been discussed in [6–8]. Due to the lack of reference data, it was necessary to start the data collection from scratch. Point clouds are uniquely suited for this purpose due to their structural properties. Their ability to capture precise geometric information and represent realistic surfaces enables a detailed and accurate representation of objects and scenes in 3D as shown in Fig. 2. This makes it a preferred format for applications such as 3D modelling, virtual reality, visualisation and simulation. The high accuracy and detail of point clouds allows complex geometry and fine surface detail to be faithfully represented in 3D. This makes them a powerful tool for capturing, analysing and displaying spatial information across a wide range of disciplines.

Data Acquisition: To construct the 3D city model of East Jerusalem, an aerial survey was conducted in September 2019, collecting a total of 571 RGBI aerial

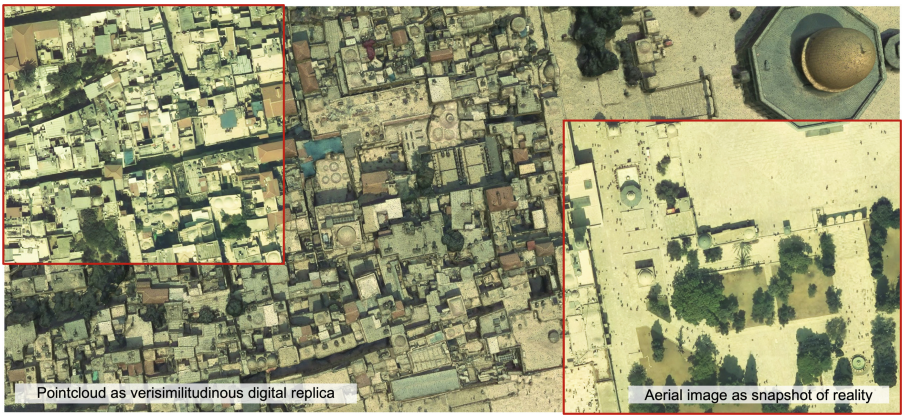


Fig. 2. Representation of a high-resolution point cloud model of the Old City of Jerusalem with real aerial photographs integrated as sections on the left and right. The quality of the point cloud is so high that it is almost indistinguishable from photographic images.

images. These aerial images had a resolution of 10cm GSD, with an overlap of 80% in the longitudinal direction and 60% in the transverse direction. In addition, approximately 3500 households were interviewed to collect semantic information such as income, demographics, etc. No reference data were available, except for the photogrammetric analysis for which GCPS (Ground Control Points) were used.

Data Processing and Integration: The process of data processing and integration to create the 3D virtual city model of East Jerusalem involved several steps to ensure that the various data sets were efficiently merged and harmonised.

Data Acquisition: The database for the 3D city model consists of a variety of sources, including aerial imagery and semantic information from household surveys. The aerial imagery was acquired through an aerial survey in September 2019, using 571 RGBI aerial images. These high-resolution aerial images, with a ground sampling distance (GSD) of 10 cm, allowed for detailed coverage of the urban environment. In parallel, a household survey was carried out to collect statistical information on different areas such as income, demographics and type of use.

Integration of Semantic Information: Further semantic and spatial data were provided by partner organisations (NGOs) or collected during the project period. These data covered different aspects such as environmental services, access to water, sanitation, waste management, transport network and land use. The semantic information was integrated into the different steps of the process (see here [6–8]) by assigning additional attributes and properties to the objects in

the 3D city model. For example, information such as type of use, height, number of residents was assigned to the buildings.

Data Integration: Integrating the various data sources was critical to creating a consistent and meaningful 3D city model. A key step in this process was the harmonised integration of aerial imagery derived 3D data and semantic information. Open source geographic information systems such as QGIS were used to import, transform and merge the data into a single coordinate system and to transfer it into a common database with a custom data model. By combining the aerial imagery derived 3D data with the semantic information, it was possible to create a accurate and detailed 3D model of the region of East Jerusalem.

Data Processing: Specialist software solutions were used to process the data. In particular, Bentley ContextCapture software was used to process the aerial imagery and reconstruct the 3D geometry of the region. Advanced algorithms were used to extract spatial information from the aerial imagery to create a high-resolution and realistic 3D model of the city. In addition, QGIS and custom software were used for further data processing and analysis, particularly for object formation, extraction, and creation. The semantic information from the household surveys was imported and linked to the 3D objects in the virtual model. QGIS provided a range of functions and tools to process, filter and analyse the data. This included assigning attributes such as building use type, height, and number of residents to semantically enrich the 3D city model for further analysis.

Hardware and Software Infrastructure: The 3D city model of East Jerusalem required a specialised hardware and software infrastructure to create, manage and deploy. High-resolution multispectral cameras and RGBI aerial stereo imagery were used for data acquisition to accurately assess and reconstruct the three-dimensional information. Data processing used powerful workstations and Bentley ContextCapture software, QGIS and custom software to generate 3D point clouds and textured meshes. Mapping and spatial calculations were performed using QGIS and custom software to convert the imagery into high-resolution 3D data and extract object information. GeoServer managed the geodatabase, while a custom database schema efficiently stored and managed the georeferenced data and models. The resulting 3D city model of East Jerusalem was made available through an online platform by combining high quality hardware and specialised software infrastructure.

Features of the 3D City Model: The 3D virtual city model of East Jerusalem incorporates several features to provide a comprehensive representation of the urban environment. These include detailed representation of buildings, streets and public facilities. The model contains semantic information such as the type of use, height, year of construction and owner associated with the buildings. It also enables the visualisation of the road network and transport infrastructure, including bridges, junctions and traffic signs. In addition, information on

public facilities such as schools, hospitals, parks and government buildings can be displayed. These features support civic participation and urban planning by enabling accurate analysis and visualisation of the urban environment. For example, city planners or architects can use the model to assess the accessibility of schools or hospitals in specific areas and make better urban planning decisions.

Web Publication of the 3D City Model: The 3D model of East Jerusalem was published on an online platform. The data was transferred and backed up by connecting the extensive geodatabase to the publisher Virtual City Systems. The data was hosted on a server in Bethlehem. For web publishing, web technologies such as HTML, CSS and JavaScript were used to provide an interactive user interface. Users were able to explore the 3D city model online, navigate and use certain features such as overlaying specific information or switching between different layers and display modes. The final 3D model with the web platform is shown in Fig. 3.

Data Quality Assurance: Data quality assurance measures were implemented to ensure accurate and high quality 3D urban modelling of East Jerusalem. This included verifying the accuracy of aerial imagery and validating semantic information from household surveys. Quality control procedures and metrics were applied to address data errors. Extensive data processing and integration resulted in an accurate 3D virtual city model. Specialist software such as Bentley ContextCapture and QGIS played a vital role in processing and analysing the data. Data quality assurance validated aerial imagery and semantic information to ensure reliability.

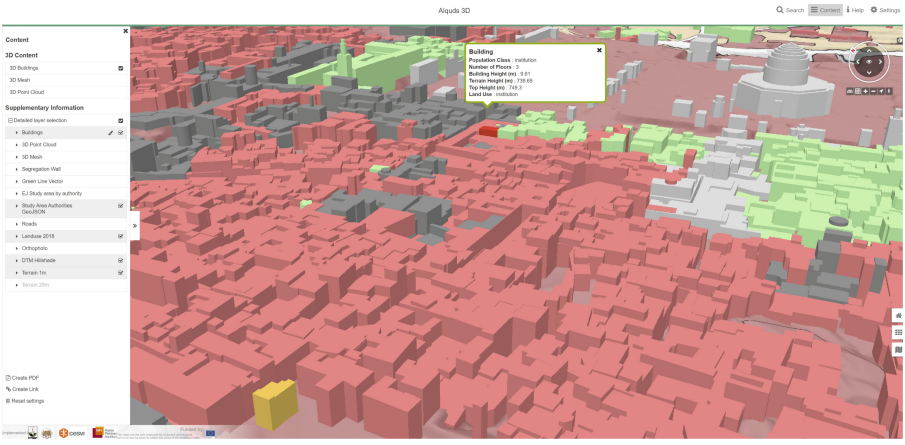


Fig. 3. Representation of the virtual 3D city model of East Jerusalem on the web platform described. The model shows detailed 3D buildings of the Old City of Jerusalem, coloured according to their function. It is a dedicated visualisation system that statically displays the pre-processed data.

4 Optimisation

A 3D virtual city model plays a crucial role in urban planning and development, providing an accurate and detailed representation of the urban fabric. It serves as a valuable tool for decision making and finding effective solutions to urban challenges. However, several factors need to be considered in order to create a functional and effective model. One important factor is data integration, which involves the consolidation of different data sources to ensure a comprehensive and cohesive representation of the city. Another factor is the abstraction of reality, where the model is required to strike a balance between capturing sufficient depth of information and enabling easy communication and understanding. The complexity of the model is also an important consideration [11,19]. It encompasses the granularity of the urban environment, such as the variety of structures, landscapes and infrastructure. Creating an optimised 3D city model requires a holistic approach that considers technical, design and user factors. Geometric simplification is a key technique for optimising the model, allowing efficient representation without compromising essential detail. The integration of heterogeneous data sources is another aspect, ensuring that different types of data are seamlessly incorporated into the model. Cartographic visualisation techniques enhance the visual appeal and usability of the model, facilitating effective communication. User interaction is essential for a user-friendly experience, allowing stakeholders to explore and interact with the model intuitively. In addition, adapting the model to specific use cases, such as virtual reality, enhances its applicability and utility. However, implementing 3D city models can be challenging. Integrating independent components and harmonising different data sources and types can be complex and require careful coordination [11,19]. Adapting proprietary visualisation platforms can have limitations, particularly in terms of dynamic capabilities and on-the-fly processing of user requests. Efforts must be made to ensure that the model is valuable for citizen participation and urban planning. Despite the challenges, maximising the usefulness of the model by integrating relevant information and analysis can greatly enhance its effectiveness. In summary, the optimisation of 3D city models is a multidisciplinary task involving various aspects such as data integration, abstraction, complexity, geometry simplification, data source integration, visualisation, user interaction and adaptation to specific use cases. By addressing these factors, 3D city models can be improved to provide realistic, efficient and user-friendly representations that benefit urban planning and development processes [20].

Optimisation of 3D city models is a vast area of research focused on improving the performance and usability of these models. Numerous scientific papers address different approaches and techniques for the optimisation of 3D city models, providing valuable insights. Santhanavanich & Coors (2020) [16] discuss dynamic 3D city models, highlighting their concepts, methods and applications. Dynamic models enable the capture and tracking of urban development changes in real time, supporting responsive decision making. The authors highlight the importance of open standards and open source software for the efficient develop-

ment and updating of dynamic models. Ledoux et al. (2021) [14] explore various optimisation techniques for 3D urban models, including geometric simplification, model size reduction and performance improvement. They find that open source software provides a cost-effective and flexible alternative to proprietary software. Girindran et al. (2020) [9] investigate the use of OpenStreetMap (OSM) to create 3D city models. They show how OSM data can be used to derive building geometries and generate models. This open source approach allows for broad participation and collaborative development of 3D city models. Xie et al. (2012) [21] address dynamic simplification of 3D city models and present techniques for adapting models to changes in urban development. Efficient algorithms and techniques are crucial to ensure real-time performance of dynamic models. Döllner & Hagedorn (2007) [3] explore the seamless integration of heterogeneous data sources for 3D city models. They discuss different approaches to achieve comprehensive and consistent modelling, highlighting the importance of efficient algorithms and techniques for the integration process. Julin et al. (2018) [12] focus on optimising the visualisation and communication of 3D city models. They emphasise the application of cartographic principles such as shape simplification, colour coding and visual hierarchies to improve the readability and comprehension of the models. Ledoux et al. (2021) [14] discuss the optimisation of user interaction in 3D city models and present methods to improve navigation, information access and interaction with the model. They highlight the importance of intuitive user interfaces and user-centric features. Sugihara et al. (2015) [18] investigate the automatic generalisation of 3D building models and present methods for simplifying complex models and adapting them to different scales. The aim is to improve readability and efficiency, especially for larger spatial domains. Döllner & Buchholz (2005) [4] specifically address the optimisation of 3D city models for virtual reality (VR) applications. They discuss techniques to reduce model complexity, improve visual quality, and integrate real-time data to create an immersive and realistic VR experience. This is particularly important for architectural visualisation and urban planning applications.

In order to improve the performance, usability and applicability of 3D city models, several important aspects should be considered during the optimisation process. The main aspects are discussed below:

- Simplify geometry: Reduce the complexity of 3D geometry using techniques such as polygon reduction and level of detail (LOD) to improve performance and visual quality.
- Data integration: Integrate disparate data sources to create comprehensive 3D city models, resolve conflicts and ensure data quality.
- Cartographic visualisation: Apply cartographic design principles to improve the readability and aesthetics of 3D city models, such as colour coding, visual hierarchies and contrasts.

- User interaction: Designing user-friendly interfaces and integrating interaction tools to improve user experience and usability.
- Quality assessment: Implementing mechanisms to assess the accuracy and reliability of 3D city models.
- Performance optimisation: Using optimised algorithms and techniques to improve the performance and real-time visualisation of 3D city models.
- Interoperability: Promoting interoperability between different systems and data sources using open standards and interfaces.
- User-centred design: Designing the user interface based on user-centred principles to enable easy and intuitive use of 3D city models.
- Data accuracy and validation: Conducting quality assessments to ensure data accuracy and validity in 3D city models.
- Semantic enrichment: Integrate semantic information to enrich 3D city models with additional contextual data.
- Multi-scale representation: Developing techniques to represent 3D city models at different scales for a comprehensive understanding.
- Real-time updates: Implementing mechanisms for real-time updating of 3D city models based on the latest developments.
- Collaborative and participatory modelling: Encouraging collaboration and participation of different stakeholders in the development and updating of 3D city models.
- Accessibility and inclusivity: Designing 3D city models to be accessible to all user groups.



Fig. 4. Representation of the virtual city model with 3D buildings, underlying land use classes and static spatial units.

In future efforts to optimise the 3D city model of East Jerusalem, an important and transformative step is to move away from the proprietary and static system provided by Virtual City Systems. As shown in Fig. 5, the 3D city model in VCS can only be displayed using a predefined style. This means that the user is severely restricted and unable to change the way the map is displayed, such as changing the layer hierarchy or making simple colour changes to objects or data. Figure 4 shows that the resulting model has some limitations. It requires the programming of certain declarative styles in the backend and does not provide any interaction or manipulation capabilities on-the-fly within the final visualisation. For example, the third dimension of buildings is little used or not used at all, although it could be used effectively as a communication medium.

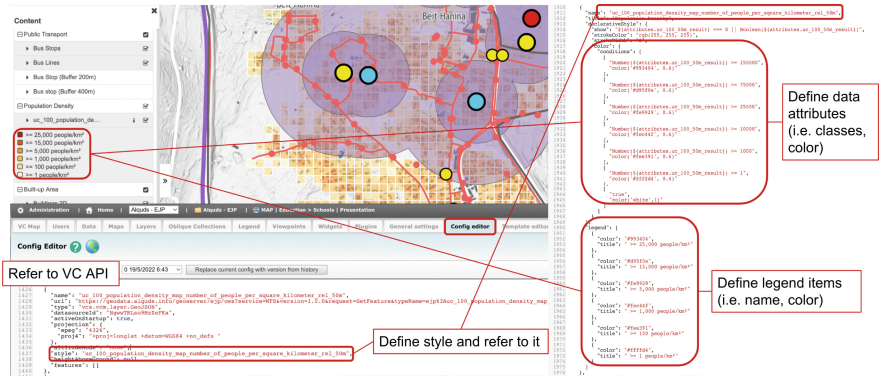


Fig. 5. Overview of the backend and map display illustrating the required elements of the declarative style.

The adoption of an open source alternative that is specifically tailored to the unique needs and challenges of the East Jerusalem region is critical. As a static system VCS system is also unable to make dynamic changes to scene content. Only previously created scenarios can be played and activated or deactivated. Due to the lack of a link to 3D data, the 3D display does not seem to make sense and in most cases a 2D map is the better communication medium as shown in Fig. 6.

This shift to open source components will allow for greater flexibility, customisation and adaptability, enabling the model to effectively capture the complex dynamics and nuances of the area. A primary goal of the optimisation process is to prioritise usability, making the 3D city model of East Jerusalem intuitively simple and easy to use. This user-centred approach is essential to ensure that a wide range of stakeholders, including non-experts and laypersons, can easily navigate and interact with the model. By improving accessibility and the overall user experience, the model will become a powerful tool for effective urban

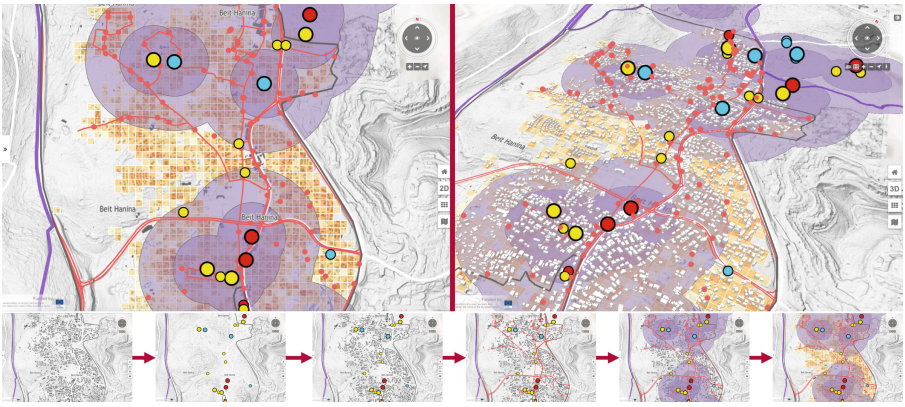


Fig. 6. Map representation of an application example with classified school locations and their catchment areas according to distance, transport infrastructure (bus network and bus stops) and underlying population density on a static spatial unit (grid). The process of merging different layers of information leads to the final map. On the left, the 2D view; on the right, the 3D view. There is a clear difference in communication and readability, with the 2D view being superior.

planning and development decision-making in the context of East Jerusalem. In addition, the implementation phase has provided invaluable lessons that will guide future improvement efforts. These lessons shed light on the specific challenges and obstacles encountered during the implementation process, such as data integration, system coordination and visualisation limitations. The optimised system should present different use cases according to their purpose in an automated and user-friendly way, make them usable accordingly and provide them automatically "on the fly", as shown in Fig. 7.

By leveraging this knowledge, future efforts can address the above challenges and develop strategies to mitigate potential roadblocks, resulting in a more efficient and successful 3D city model optimisation process. By using open source solutions and focusing on usability, the optimised 3D city model of East Jerusalem will provide a comprehensive and customised platform for stakeholders to explore, analyse and make informed decisions about urban planning and development. The model will facilitate collaboration and engagement between different stakeholders, including citizens, government officials and urban planners, promoting a participatory approach to decision-making. This will ultimately contribute to the sustainable growth, development and preservation of the unique cultural, historical and geopolitical aspects of East Jerusalem.

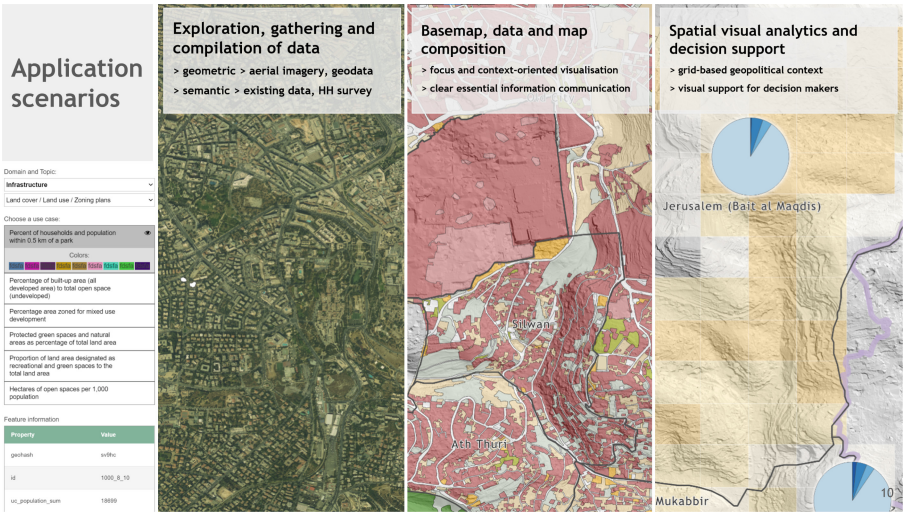


Fig. 7. Different uses for East Jerusalem, illustrated in three scenarios. Left: Simple 2D and 3D presentation for realistic exploration, data collection and orientation. Middle: Thematic map display, e.g. land use, for focus and context to enable clear communication of information. Right: Static spatial unit as a basis for complex geostatistical analysis and data enrichment for visual analysis and decision support.

5 Concluding Remarks

In conclusion, this study has presented a comprehensive workflow for optimising the 3D virtual city model of East Jerusalem to facilitate community-based urban development. By applying various methods such as data processing, integration and validation, the quality, accuracy and efficiency of the model were improved. The use of open source software played a key role in providing a cost-effective and flexible solution. The optimised 3D city model of East Jerusalem offers numerous benefits for urban planning and decision-making. It enables the analysis of urban planning challenges, supports decision-making processes, engages citizens and stakeholders, and predicts the impact of urban development policies. It serves as a valuable tool for creating sustainable and effective planning policies in the region.

However, it is important to recognise the challenges and limitations associated with optimising the 3D city model. Technical limitations, privacy and security requirements, and stakeholder engagement and participation need to be carefully considered to achieve the desired outcomes. Ongoing maintenance, updating and adaptation of the model is essential to ensure its optimal performance and usability. Future research in 3D city model optimisation should focus on further improving the methods and technologies used. This includes the development of open source software, the integration of real-time data and artificial intelligence, and the consideration of stakeholder requirements and needs.

Collaboration between experts in urban planning, geoinformatics and data processing is essential to continuously improve and adapt the model. In this way, better decisions can be made and the sustainable development of East Jerusalem can be promoted.

In conclusion, the optimised 3D virtual city model of East Jerusalem developed in this study provides a robust framework for community-based urban development. The transferability of the workflow and the use of open source software enable cost-effective and efficient solutions for data collection, processing and visualisation. This contribution improves the availability of high quality 2D/3D databases for urban planning, ultimately promoting sustainable urban development not only in East Jerusalem, but also in other urban regions.

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