A digital twin based on Land Administration

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Key words: 3D land administration, Visualization, LADM, Digital Twin

SUMMARY

As urban architectural environments become increasingly complex and densely populated, the demand for precise registration of legal statuses, encompassing both private and public interests, has become more urgent. Traditional 2D cadastral registration systems are increasingly inadequate for addressing the multifaceted and vertical nature of modern urban landscapes. These systems are limited in scope and unable to fully capture the intricacies of multi-level property rights, overlapping parcels, and underground constructions.

This study uses a BIM/IFC model for the building's physical representation. The party and Rights, Restrictions, and Responsibilities (RRRs) data are stored in a DBMS following ISO 19152-2 (Land Administration Domain Model, LADM) All data and the building location are fictitious and represent the most important categories of Land Administration cases. Visualization and interaction is achieved in 3D over the web using Cesium JS, an extensible globe viewer.

Unlike earlier 3D cadastral systems, this research has developed a new 3D Land Administration prototype based on the complete scope of LADM and not just focusing on the 3D spatial information. The objective is to explore improved methods for analyzing and visualizing RRRs in complex buildings. Novel techniques include presenting UML instance-level LADM diagrams for selected parties and/or apartments, showing RRRs and BAUnits linking them to the spatial units. The study further introduces a new method for displaying surrounding buildings at varying Level of Detail (LoD), with closer buildings rendered in higher detail and more distant buildings shown in less detail. This selective detailing enhances both performance and clarity in visualizations.

A key feature of this digital twin system is its real-time update capability. The prototype developed in this study supports the updating of party and rights information in the backend database, accurately reflecting these updates in the public front-end version. This ensures the maintenance and visualization of the most current property rights data. The system also integrates sunlight simulation, which is crucial for urban planning, architectural design, and aiding buyer decision-making. The prototype is (still) online available at https://www.gdmc.nl/LADM3Dview/ and via a usability study evaluated.

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1. INTRODUCTION

The rapid growth of urban populations and the corresponding expansion of city infrastructures have triggered a fundamental reevaluation of spatial utilization strategies in contemporary urban environments. This growth often pushes cities to expand not only horizontally but also vertically into the sky and downward into the earth. Such multidimensional expansion has become crucial in densely populated urban centers, where the availability of land for housing and infrastructure is severely limited. This limitation naturally drives the development of multi-story and vertical buildings to maximize the efficient use of space.

This study is motivated by the critical need for efficient and transparent management of urban land, particularly in vertical developments. Traditional land management systems, which are largely two-dimensional, are increasingly challenged to manage the complexity inherent in vertically integrated property rights. The representation of parcels in 2D maps of multi-layered overlapping properties is handled by dividing the map into multiple parcels. Each parcel illustrates various rights. This method may be straightforward for those involved in property registration, but it can be difficult for those unfamiliar with the actual scenario to understand (Broekhuizen, et al., 2021).

Against this backdrop, this study is dedicated to exploring and implementing an innovative land management solution focused on the visualization of apartment rights. A prototype 3D Land Administration System (LAS) is developed that not only integrates the physical and legal spatial models of multi-story apartments but also dynamically displays LADM data on a web interface. This enables users to intuitively query apartment units and their associated legal information, such as ownership, usage restrictions, and responsibilities. Moreover, the system allows various stakeholders—including real estate developers, governmental agencies, buyers, and sellers—to access and update information, thereby ensuring the timeliness and accuracy of the data.

By integrating modern GIS technology with land management standards, this study's information system prototype not only enhances the transparency of land management but also deepens users' understanding of apartment rights and the LADM framework. Furthermore, it provides a valuable reference and foundation for the development of future technologies and policies related to this field.

This paper aims to provide an overview of the research background, motivation, and objectives, with a focus on exploring a digital twin platform based on land administration. Section 2 examines existing 3D land administration systems, explaining how this study builds upon and innovates previous work. Section 3 discusses the methods used for visualizing apartment rights and Section 4 presents the results of usability testing. Finally, Section 5 summarizes the research findings and suggests potential directions for future research.

2. RELATED WORK

A land administration system is a modern, parcel-based land information system that maintains records of land interests, including Rights, Restrictions, and Responsibilities (RRRs). Typically, it comprises a geometric description of land parcels, linked to additional records that explain the nature, ownership, or control of these interests, as well as the value of the parcels and any improvements. It can be used for fiscal purposes, such as valuation and fair taxation, for legal purposes like property conveyancing, to aid in land and land-use management, including planning and administrative tasks, and to promote sustainable development and environmental protection (FIG, 1998). The fundamental entities in cadastral registration are "real estate", "immovable property" or "property", and "subjects" (Stoter, 2004). Typically, land and the buildings on it are called real estate. The various rights associated with the land are termed real property (FIG,1998). The Land Administration System (LAS) aims to provide a foundation for land management by integrating spatial, legal, and administrative data. Notably, the term "3D Land Administration" is increasingly favored over "3D Cadastre" because it encompasses the entire scope of land registration and cadastral work (Kalogianni, et al., 2020). The adoption of 3D LAS is driven by the fact that a 2D representation of ownership in complex apartments may be insufficient to fully describe and register these rights (Atazadeh, et al., 2017).

The research by (Cemellini, et al., 2020) presents a 3D LAS prototype that significantly enhances the visualization and management of 3D cadastral parcels and utilizes Cesium JS to visualize 2D and 3D data in a 3D format, aiming to better represent legal boundaries and visualize underground spaces; see Figure 1. However, users encountered a single level of detail and administrative information was presented in table form (and not in intuitive graph of instance level diagram). The 3D model, not being based on Industry Foundation Classes (IFC) data, lacked sufficient detail and did not include the surrounding environment of the studied buildings. This study focuses on usability testing and continuous improvement based on user feedback, demonstrating the effectiveness of a user-centered design approach.

Additionally, this research references the list of functionalities for 3D visualization of cadastral data presented in the work of Cemellini et al. (2020).

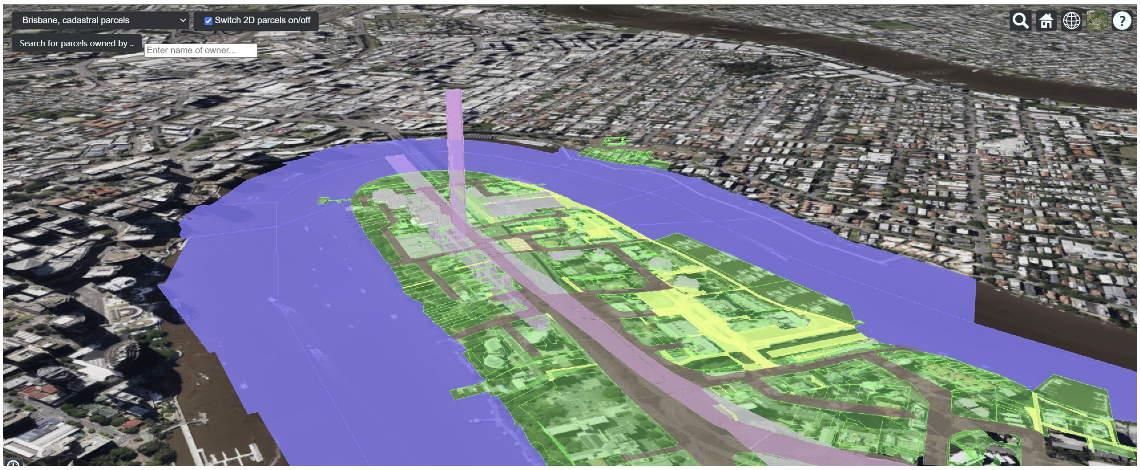

Figure 1. Visualization of the urban area using Cesium JS (system online at http://pakhuis.tudelft.nl:8080/edu/Cesium-1.43/Apps/3dcad/)

The 3D LAS system described in OGDB (https://bpd2.ogdb.nl/bpd/project/9531/landgoed-hoevesteijn) provides both physical and legal models that can be displayed separately; see Figure 2. This system supports interactive functionality, allowing users to click on each apartment unit to retrieve specific information. Additionally, it includes sunlight simulation for individual buildings. However, it does not account for the shadowing effects of surrounding buildings and does not incorporate the LADM.

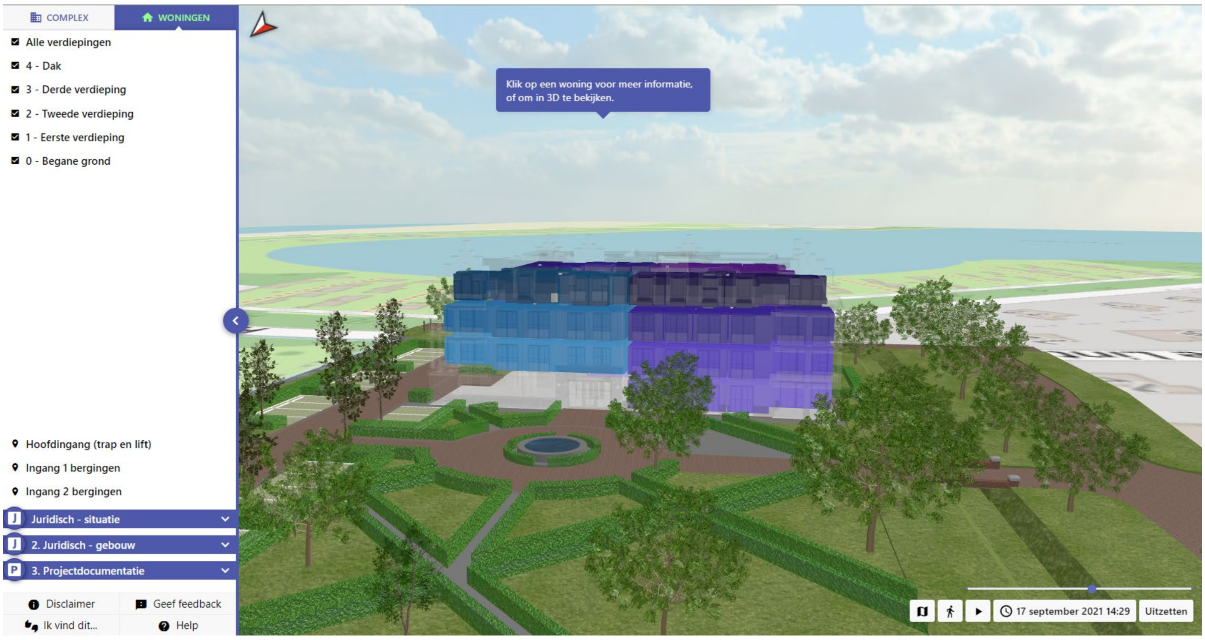

Figure 2. 3D LAS system interface showing physical and legal models (system online at https://bpd2.ogdb.nl/bpd/project/9531/landgoed-hoevesteijn)

The study by Broekhuizen added legal information based on LADM to IFC models, stored it in a spatial database, and visualized it on a 3D platform. However, all the LADM information is provided to users in tabular form (Broekhuizen, et al., 2021); see Figure 3.


Figure 3. Visualization of legal information based on LADM in a 3D platform

3. SYSTEM DESIGN PRINCIPLES

This section introduces the main system design principles (components) to be used in the development: Digital Twin approach, specific requirements of 3D Land Administration Systems, and the used system integration and implementation strategies.

3.1 Digital twin

The term Digital Twin (DT) was first used by the National Aeronautics and Space Administration (NASA) in technology domains such as modeling, simulation, information technology, and integrated technology roadmap. NASA's Apollo program introduced the concept of "twins," referring to two identical spacecraft built to mirror the condition of the spacecraft for the mission duration (NASA, 2010).

Digital twins digitally represent real-world scenarios. The most advanced urban digitization method appears to begin with 3D city information models (Schrotter & Hürzeler, 2020). These models primarily describe the urban physical environment's state. However, there is widespread consensus that digital twins are not merely equivalent to 3D city models; they also include attributes such as lifecycle management of individual urban objects and assets (Lehtola, et al., 2022).

This study presents a sophisticated 3D system that accurately replicates the physical structure of an apartment building and its individual rooms. The system allows users to interactively select any apartment to access real-time updates of basic apartment information and Land Administration Domain Model (LADM) information, ensuring that legal data is dynamically synchronized with the physical world.

A key feature of this system is its advanced sunlight simulation capability. It follows the system's current time and enables users to simulate sunlight and shadow effects for any specified time. This functionality supports architects in optimizing their designs and aids potential buyers in assessing room lighting conditions. By providing dynamic visualization and real-time updates, this 3D system significantly enhances decision-making processes, showcasing the practical applications of DT technology, such as real-time data integration, predictive analysis, and effective decision support.

3.2 Requirements of 3D Land Administration Systems

A 3D LAS is structured into three distinct layers to optimize performance and user interaction. The Presentation Layer serves as the system's front-end, directly interacting with users. It includes land administration features that visually represent critical data such as property boundaries and ownership details, alongside visualization features equipped with dynamic scaling, rotation, and other interactive elements to enhance user engagement. The Application Layer includes non-functional components that bolster technological diversity, system interoperability, and overall usability. These features, while not directly tied to visualization, indirectly uplift the visual quality by ensuring system robustness and seamless integration with diverse technologies. This layer acts as a bridge between the user interface and backend data management. The Data Access Layer ensures data accessibility and supports format conversions. It links to spatial databases, flat files, and web services, essential for versatile and scalable data management in various formats. Collectively, these layers form a comprehensive system that facilitates effective data visualization and enhances system reliability and user experience in land administration (Shojaei, et al., 2013).

3.3 System Integration and Implementation

The primary challenge addressed in this study revolves around the visualization of legal data on the front end and the precise integration of legal models with physical models within a 3D Land Administration System (LAS). Achieving a functional and efficient system necessitated a comprehensive approach encompassing several critical steps.

Data standardization was a fundamental aspect of the integration process, ensuring seamless interoperability between different data sources. To facilitate this, legal data was formatted according to the ISO 19152:2012 standard, which governs the representation of land administration data. Concurrently, spatial models were formatted in either IFC or OBJ, ensuring compatibility with the system. This dual approach to standardization allowed for the effective combination and visualization of diverse data types within the 3D LAS.

The development of the user interface (UI) was another crucial component, designed to enhance user interaction and experience. The UI was created using Vue.js and Cesium, chosen for their capabilities to provide an interactive and intuitive interface. This choice of technologies was instrumental in delivering a user-centric design that facilitated ease of use and engagement with the system.

Backend development and data handling formed the backbone of the system's operation. The backend was constructed using Node.js, which managed data requests and served as the intermediary between the frontend interface and the PostgreSQL database. This architecture ensured efficient data processing and retrieval, supporting the system's overall functionality and performance.

4. SYSTEM DEVELOPMENT

This research presents the development of a 3D mapping application that integrates Cesium within the Vue.js framework. By leveraging Vue's component-based architecture, various objects and methods from Cesium were effectively encapsulated. The development process involves several critical technical steps, as illustrated in Figure 4. The application enables the visualization of apartment building models, including their legal spaces, and allows users to access detailed ownership information for each apartment unit. The ownership information is structured based on the Land Administration Domain Model (LADM), ensuring standardized property data representation.

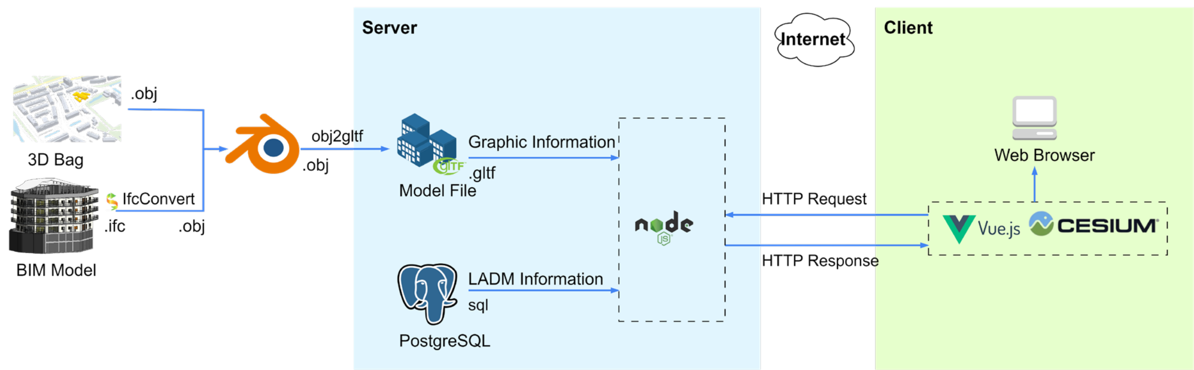

Figure 4. Web-Based 3D Visualization Architecture

4.1 Data Collection

The system employs a 3D BAG dataset in OBJ format, which includes three levels of detail: LoD1.2, LoD1.3, and LoD2.2. Apartment models, initially in Industry Foundation Classes (IFC) format, are utilized for sharing and exchanging construction and building data. All models were adjusted for accurate 3D positioning using Blender. By modifying the origin of each model, alignment with the WGS84 coordinate system was achieved. For integration with Cesium, the models were converted to the glTF format. This conversion was accomplished using the obj2gltf tool from Cesium and IfcConvert from IfcOpenShell.

4.2 Adaptive Level of Detail

The system features an "Adaptive LoD" functionality that adjusts the visualization of the surrounding area based on the distance from the central building. This approach enhances both efficiency and clarity by varying the model complexity according to proximity. In Blender, modifications were made to set different Levels of Detail (LoD) based on distance. Specifically, LoD2.2 is used for areas within 200 meters, LoD1.3 for areas between 200 and 300 meters, and LoD1.2 for areas beyond 300 meters. Users can toggle between these levels of detail using the "Adaptive LoD" button. This feature improves the user experience by enabling high-detail visualization close to the building and reducing detail for distant areas. This dynamic adjustment optimizes performance and maintains visual clarity, as shown in Figure 5.

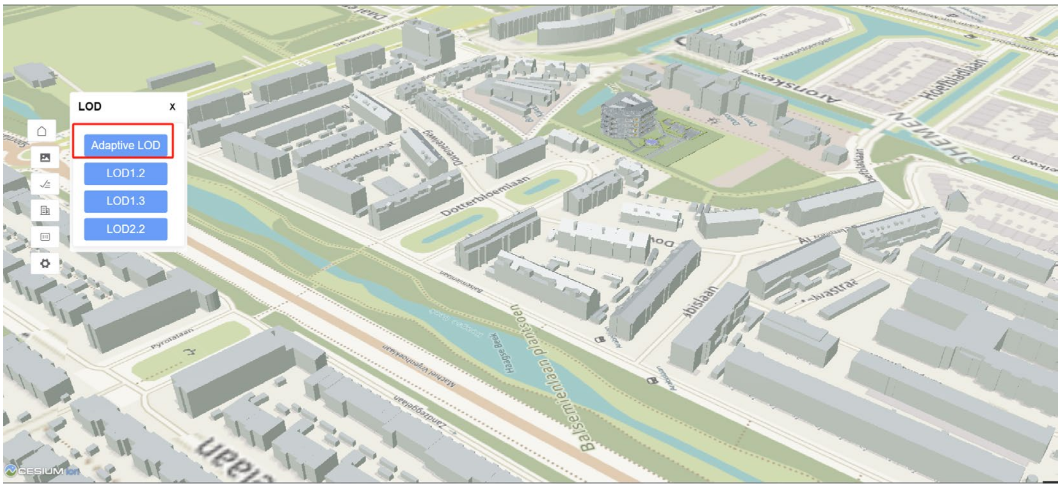

Figure 5. Adaptive LoD Visualization in the 3D LAS System

4.3 Sunlight Simulation

To achieve realistic sunlight simulation, the system utilizes Cesium's global lighting feature, which dynamically adjusts the scene's illumination based on the sun's position. This adjustment enhances the scene's visual realism, reflecting actual solar conditions. A custom function was developed to control lighting effects further, determining whether it is day or night based on the positions of the sun and camera. This function adjusts the lighting intensity to accurately represent day and night conditions, significantly improving lighting realism, as illustrated in the comparison between scenes with and without this function. Additionally, shadow effects were enabled to enhance the scene's depth and realism. Cesium's automatic settings synchronize the scene's time with the system clock, enabling real-time lighting and shadow rendering. To further improve user interaction, a date and time selection feature was incorporated, allowing users to choose specific dates and times, as shown in Figure 6.

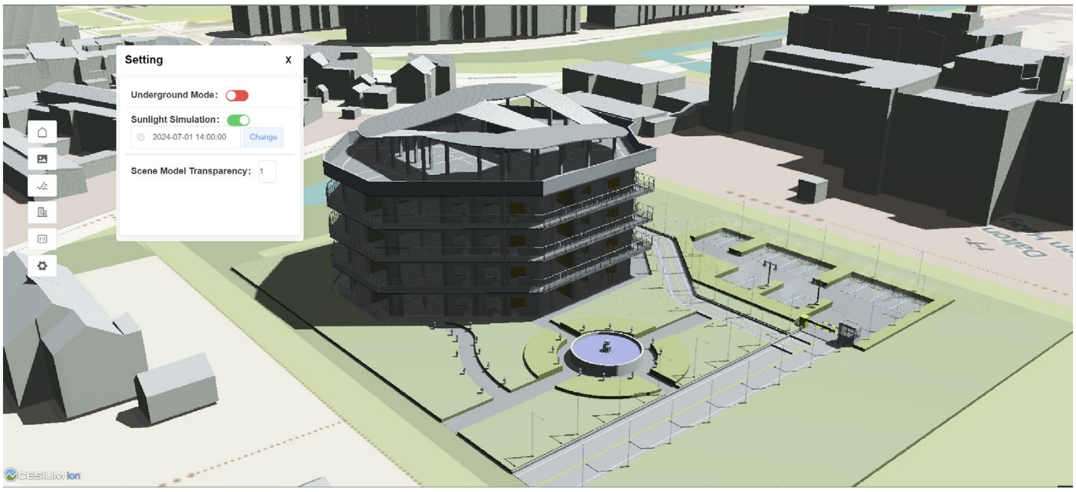

Figure 6. Sunlight Simulation Effect

This combination of dynamic lighting adjustments, shadow effects, and interactive date and time selection creates a highly immersive environment, making it ideal for applications in architectural design and real estate decision-making. Users can observe how various times of the day influence lighting and shadows, providing a realistic simulation for better decision-making.

4.4 Visualizing Apartment Model

The platform supports the visualization of both 3D physical models and legal space models for condominium ownership. Inspired by the https://bpd2.ogdb.nl/bpd/project/9531/landgoed-hoevesteijn project, users can toggle the display of physical and legal spaces on and off. This feature provides valuable context, enabling users to better understand the location and extent of legal spaces in relation to their corresponding physical structures. By incorporating physical spaces into the visualization, the system effectively demonstrates the relationship between legal boundaries and the actual built environment, enhancing users' comprehension of condominium ownership and the associated rights.

Additionally, the platform includes functionality for visualizing underground spaces. The underground space visualization feature can be activated by selecting the Underground Mode button. This capability draws inspiration from the globe translucency example provided by Cesium Sandcastle. To enable camera navigation into underground areas, camera collision detection is turned off. This adjustment allows the camera to move seamlessly into and through the underground spaces. To enhance visibility of these spaces, the transparency of the globe is adjusted. This configuration makes the globe more transparent based on the camera's distance, thus allowing users to see through the globe and observe underground structures. The effect of this function is demonstrated in Figure 7.

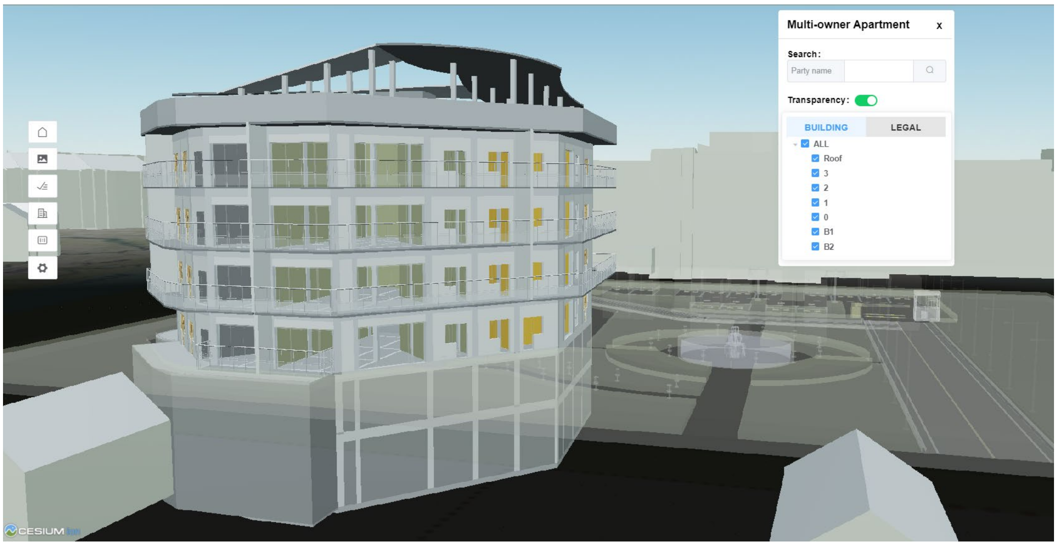

Figure 7. Visualization of underground spaces

4.5 LADM Chart Visualization

This study visualizes legal scenarios using instance-level cases from ISO 19152:2012 and examples by (Lemmen, et al., 2022). UML instance-level diagrams are created to illustrate various legal scenarios in the 3D land administration system. Figure 8 shows a UML instance-level diagram for a hypothetical case where James and Bella jointly own an apartment and a parking lot. Figure 9 presents another hypothetical scenario where homeowner Jack rents three apartments to Sophia, Mia, and Ella. Additional examples include a scenario where an apartment owner secures a loan from a bank during the purchase and a transaction involving both previous and current apartment owners (available online https://www.gdmc.nl/LADM3Dview/).

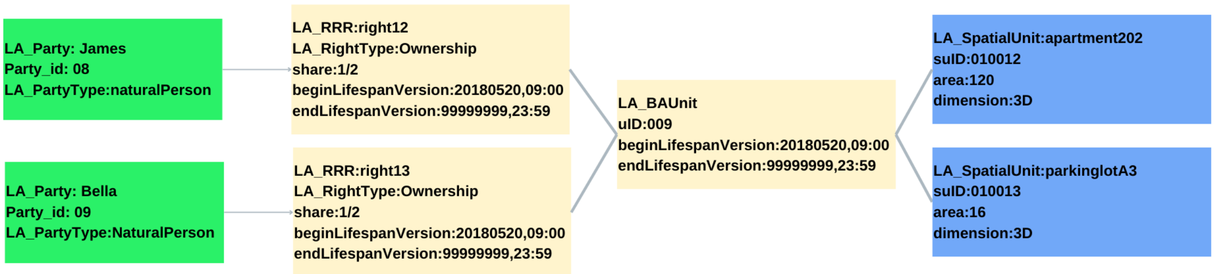

Figure 8. LADM Information of James and Bella

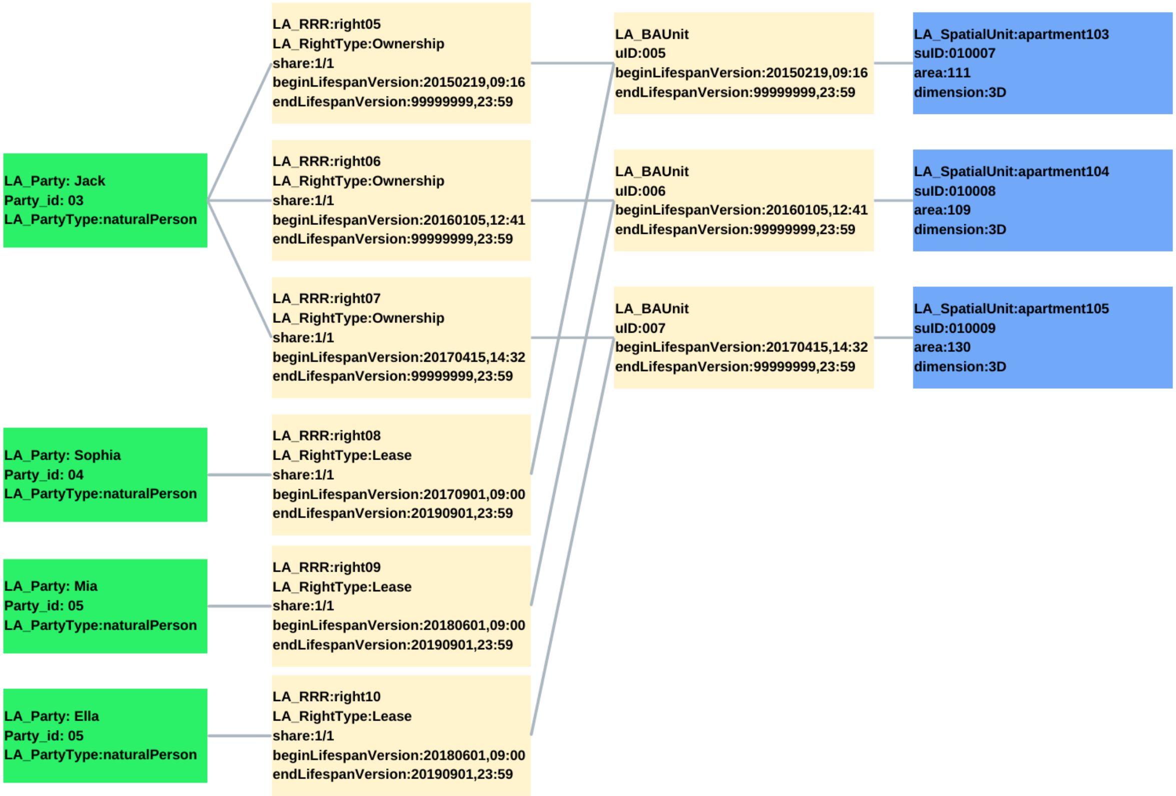

Figure 9. LADM Information of Jack

In this system, each model is assigned a unique ID upon loading, which is used for subsequent queries and processing. A click event handler is set up to detect user interactions, retrieving the model's ID when clicked. This ID is then sent to the SelectInfo component, which updates its display with information related to the clicked model. The basic information for each apartment unit is stored in a JSON file, with each unit assigned a unique ID. LADM data is maintained in a database, which, upon opening the platform, is organized into two map structures: one keyed by apartment unit IDs and the other by party names. This setup supports two modes of querying—by unit ID or by party name—ensuring comprehensive and flexible access to information. The process then involves custom methods to collect all relevant information. Finally, the getAntVG6Data method is used to convert the collected data into the AntV G6 graph format, organizing nodes and edges to accurately represent the relationships and details of the properties and individuals involved. This approach ensures that the graph is effectively visualized and remains updated in real-time as the database content changes.

5. REFLECTION

As mentioned in the requirements and the development, the frontend features an interactive graphical representation, supported by AntV G6, for visualizing relationships within the LADM data in the form of a instance level diagram of a selected subset). This tool handles data conversion and display, transforming input data into nodes and edges that illustrate complex property relationships and rights structures. The graph is designed to handle updates dynamically, ensuring that it accurately reflects any changes in the database. When the user clicks the "Query" button, the information view in the lower-left corner of the system refreshes to display a list of all properties owned by the selected individual, as shown in Figure 10. The system also supports viewing previous owner/property transaction information, as illustrated in Figure 11.

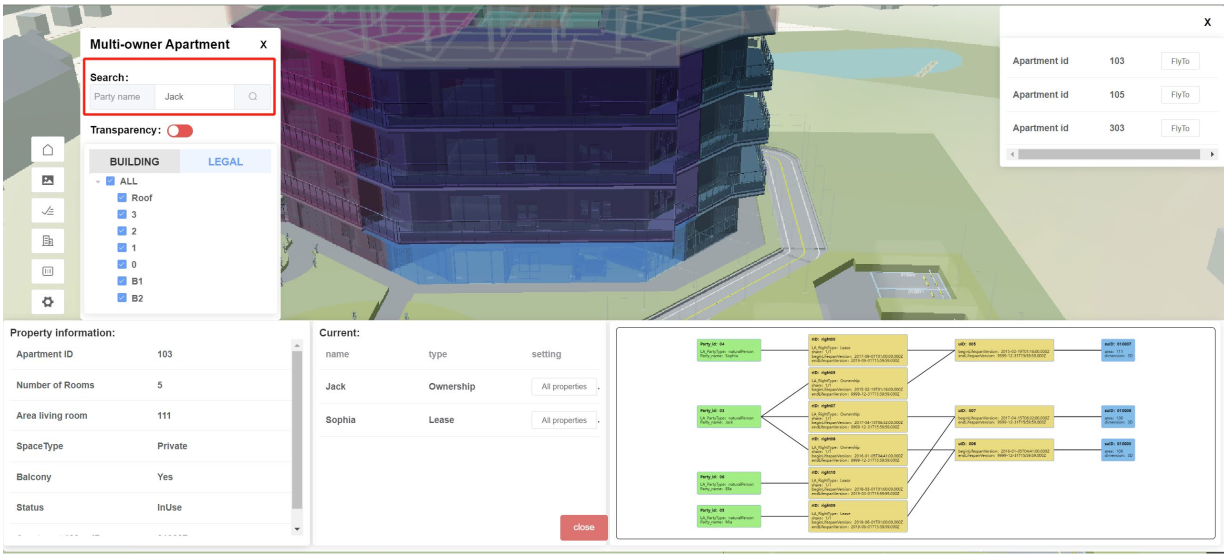

Figure 10. Search by Owner Name

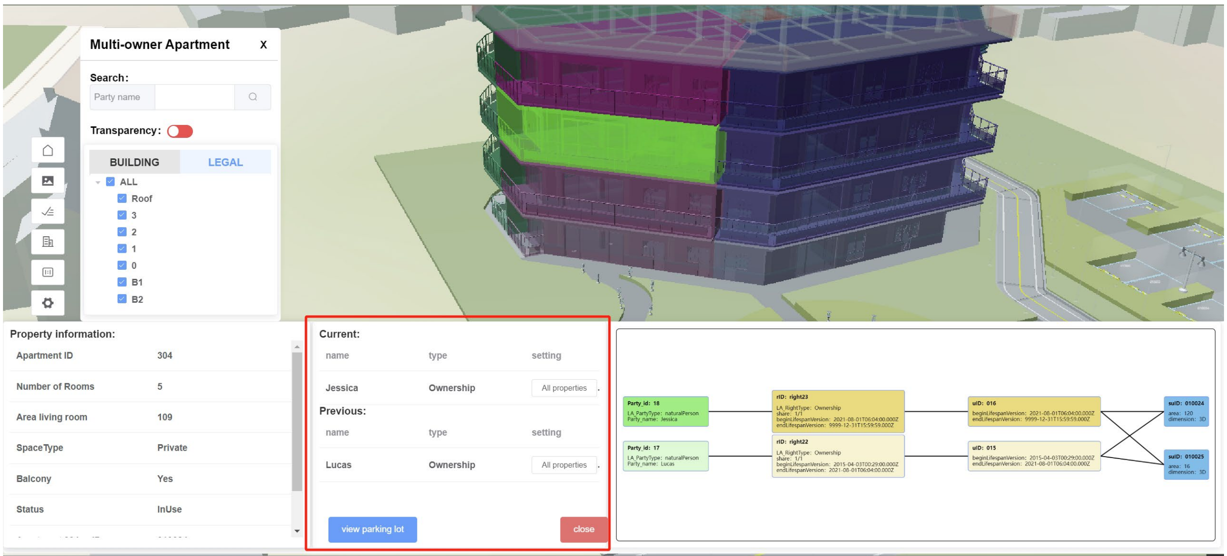

Figure 11. Show property transaction information (new owner/right in bright color, old owner/right in light colors in the LADM instance level diagram)

5.1 Usability testing

This study evaluates the usability of the system by assessing users' ability to accurately respond to questions while simultaneously rating the system during the feedback collection process. It is crucial to acknowledge that the participants involved in this usability test do not fully represent the broader user base. Nonetheless, the test effectively gathered valuable

feedback, enabling the identification of both strengths and weaknesses within the current system and highlighting areas for future improvement.
The participant groups were categorized based on their familiarity with the Land Administration Domain Model (LADM), including individuals who are familiar with LADM, those with limited knowledge of LADM, and individuals who are completely unfamiliar with LADM. To collect comprehensive feedback, specific tasks were defined for the users to perform, and corresponding questions were designed to evaluate their interactions. The tasks were carefully crafted to be clear and non-misleading, with straightforward prompts to assist users in locating the relevant controls. The tasks included switching base maps, panning, zooming, and rotating the view to identify target areas, testing 3D scene operations; controlling floor visibility; visualizing underground spaces; viewing LADM information; and simulating sunlight at various times of the day.

5.2 Test Results

Figure 12 shows the familiarity of the 24 participants with LADM. The majority of participants were either generally familiar or not familiar with LADM, with only a small portion being experts. This distribution helps in understanding how different user groups interact with the system and provides insights into usability across varying levels of familiarity.

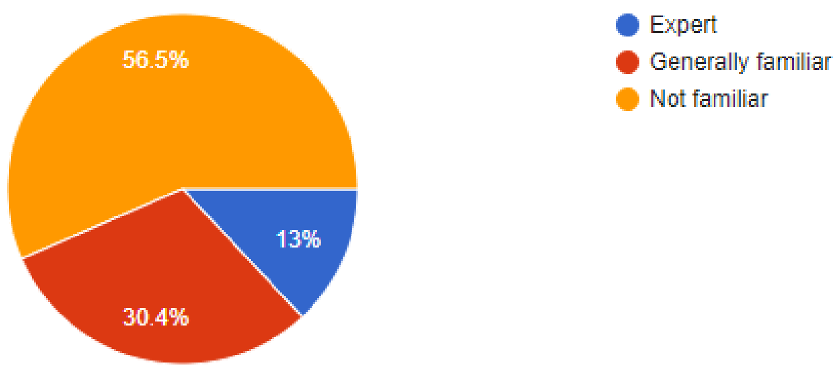

Figure 12. Pie chart of three types of participants

Test results show that in general the users were quite stratified with the available functionality and they assessed the various components with a mark on a 10-point scale:

- Navigation (panning, zooming, rotating): 8.3
- Floor visibility and underground space: 9.5
- Viewing ownership information: 9.2
- Lighting simulation: 7.0

Although the overall ratings are positive, further analysis reveals interesting differences in how users perform various tasks. For example, users found the lighting simulation feature somewhat challenging, resulting in a lower rating of 7.0. Feedback indicates that this issue stems partly from the need for more intuitive control buttons and partly from the time zone discrepancy. The platform's sunlight simulation uses Dutch time zones, but when users access the platform, it defaults to the system time of their computers, causing some confusion.

Additionally, users who are more familiar with LADM generally complete tasks more quickly and make fewer errors, particularly noticeable when viewing LADM information. In contrast, users less familiar with LADM often need more time to interpret graphical information, which affects their performance on this task.
In the final two questions of the usability test, participants were specifically asked for their suggestions on system improvements and their difficulties with terminology. The first question was, “If this digital twin system were to be redesigned, what features would you suggest?” The second was, “Did you encounter any difficulties understanding the terminology used in the system?” The responses provided valuable insights. For instance, users recommended replacing the current time selector with a more interactive time slider to improve timeline navigation. They also suggested making the search functionality more intuitive by enabling the Enter key for searches and providing clearer case sensitivity prompts. Additionally, for tasks involving 3D navigation, users proposed adding a first-person view option to facilitate easier exploration of building interiors. Because basic information about LADM was provided at the beginning of the usability test, understanding the terminology did not pose a challenge for the participants.

6. CONCLUSION

The 3D LAS developed in this study offers a range of features, including the integration and display of 3D BAG and BIM models, interactive functionalities, floor visibility control, sunlight simulation, dynamic slicing views, and underground space visualization. Most importantly, it provides dynamic, real-time UML instance-level LADM diagrams for selected parties and apartments, displaying the relationships between RRRs and BAUnits. The results have been evaluated via an usability study. Besides confirming the usefulness of the various developed 3D Land Administration interaction and visualization techniques, this also raised more wishes for future work. In future work, several key areas could benefit from further investigation to advance the capabilities and applicability of the 3D Land Administration System (LAS) developed in this study:

- Firstly, the legal data employed in this research was hypothetical and simplified, primarily for demonstration purposes. Real-world legal data is inherently more complex, and addressing this complexity poses significant challenges. Future research should therefore focus on real-world legal data, ensuring that the system can accommodate the varied and detailed nature of legal information encountered in practical applications.
- Additionally, while the current study integrates legal data with 3D models, there is potential for further enhancement by incorporating graphic data, such as Building Information Modeling (BIM) directly into the database as explored by Yang (2024).
- Another promising direction for future work involves expanding the system's capabilities to encompass various types of 3D legal spaces. For instance, the inclusion of airspace rights, underground utility networks, and mining concessions. Such advancements would enable the system to accurately represent and manage these complex legal domains, broadening its applicability and utility.
- Finally, extending the system to incorporate valuation and spatial plans in 3D, in alignment with the new Land Administration Domain Model (LADM) Parts 4 and 5,

could significantly enhance its functionality. This extension would involve creating valuation models, tools for spatial plan development and management, and ensuring compliance with the updated LADM standards.

Overall, these avenues for future research and development hold the potential to refine and expand the 3D LAS, ultimately leading to more sophisticated and practical applications in the field of land administration.

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