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Urban Landscape Digital Twin Implementation Challenges: OpenUSD Ecosystem's Solutions

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Abstract

Urban Landscape Digital Twins (ULDT) represent a paradigm shift in urban planning and development. These innovative constructs transcend mere depiction; they seamlessly blend emulation, forecasting, optimization, and real-time control of the physical urban space. Leveraging continuous connectivity, advanced mapping techniques, rigorous analysis, and interactive interfaces, Digital Twins (DT) transcend the constraints imposed by diverse physical conditions. Through the integration of multidimensional models and comprehensive datasets, they not only mirror the urban environment but also empower decision-makers to navigate its complexities with unprecedented precision and foresight. This transformative capability marks a departure from traditional urban modeling approaches, ushering in an era where the digital representation becomes an active participant in the on-going evolution of urban landscapes. Key to achieving this is the acquisition of accurate and current data from diverse sources such as photography, satellite imagery, or Light Detection and Ranging (LiDAR) technology to landscape scene assembly thanks to computer vison processing. This paper advocates for the adoption and application of the Universal Scene Description (USD) framework in urban simulation, recognizing its potency in representing large-scale 3D models with unparalleled geometric and visual fidelity. Originating from Pixar Animation Studios and recently renamed to OpenUSD, USD stands out as an open-source technology providing a standardized approach for the representation and exchange of scalable 3D data. The exploration herein delves into the rationale behind choosing USD for urban 3D simulation, elucidating its advantages and es-essential considerations. Additionally, the paper highlights the convergence points between 3D geo simulation and virtual geographic environments, casting light on challenges associated with integrating USD with various geospatial data formats. The insights provided herein contribute to a deeper understanding of the role USD plays in revolutionizing urban digital twin processing, positioning it as a pivotal tool in advancing the field of urban simulation.

Keywords: Urban Visual Feature, Universal Scene Description, Urban Digital Twin, Geosimulation; Urban Visual Computing

Abbreviations: LiDAR: Light Detection and Ranging; DT: Digital Twins; ULDT: Urban Landscape Digital Twins; NASA: National Aeronautics and Space Administration; BIM: Building Information Modeling; VR: Virtual Reality; AR: Augmented Reality; IOT: Internet of Things

Introduction

The contemporary urban landscape is a dynamic tapestry of interconnected systems and structures, subject to rapid transformation and complex interdependencies. In response to the ever-growing challenges of urban planning and development, the integration of innovative technologies has become imperative. Among these, the concept of Urban Landscape Digital Twins has emerged as a transformative force, offering a comprehensive and real-time digital representation of urban environments. The DT philosophy has been used since the 1960s by the National Aeronautics and Space Administration (NASA) and the concept of was definitively consolidated by Michael Grieves in 2003 [1,2]. According to Grieves, a DT model must contain three main parts: the physical assets, a virtual model, and the connections of data and information that tie the virtual and real spaces together. The concept of DT has a rich history, with roots dating back to the 1960s, notably employed by the National Aeronautics and Space Administration (NASA). The definitive consolidation of this concept occurred in 2003 through the insights of Michael Grieves [1,2]. Grieves articulates that a DT model is fundamentally comprised of three key elements: the physical assets, a virtual model, and the intricate network of data and information that establishes the crucial linkages between the virtual and real domains. As dynamic virtual counterparts, DT extends beyond the mere depiction of urban spaces. They encapsulate the ability to emulate, forecast, optimize, and control the physical landscape through sophisticated real-time connectivity, mapping, analysis, and interaction. However, the realization of ULDT is not without its formidable challenges. This paper delves into the intricate terrain of implementing ULDT and navigates the obstacles encountered in their development.

The focus extends beyond conceptualization to the pragmatic application of these digital twins in urban planning, architecture, and engineering. A central facet of this exploration is the examination of the OpenUSD ecosystem as a robust solution to the multifaceted challenges inherent in the implementation of ULDT. Indeed, in urban planning and development, the necessity for accurate and realistic representations of the built environment is paramount. The complexities involved in modeling visual features, encompassing materials, textures, and lighting, underscore the need for advanced technological solutions. Open USD, an open-source technology developed by Pixar Animation Studios, emerges as a pivotal player in this arena [3-6], offering a standardized approach for the representation and exchange of scalable 3D data [7-9]. Its capability to handle large-scale urban models with high geometric and visual fidelity positions it as a formidable tool for addressing the challenges faced in the implementation of ULDT. The organization of the paper is designed to provide a coherent and comprehensive exploration of the key aspects surrounding this subject matter. Section 2 provides a historical overview of the inception and ULDT. It delves into the early motivations and technological developments that paved the way for the emergence of ULDT, highlighting key milestones and pioneering projects that set the stage for contemporary applications.

Transitioning from the historical and conceptual foundation, section 3 probes into the contemporary challenges faced in implementing ULDT. It outlines the technical hurdles, such as data integration, scalability, interoperability, and security, that impede seamless ULDT deployment. With a focus on addressing the identified challenges, this section advocates for the utilization of Open USD as a robust framework for ULDT modeling. It delves into the merits of Open USD, highlighting its open-source nature, standardized approach, and capability to handle large-scale 3D models with high fidelity. t provides a step-by-step guide, encompassing data acquisition, processing, and integration, offering insights into how OpenUSD can be practically employed to overcome the challenges outlined earlier. Section 4 outlines the experimental parameters, detailing the specific settings, configurations, and data sources utilized in the implementation of OpenUSD for ULDT modeling. It aims to provide transparency and reproducibility for future researchers and practitioners interested in similar applications. The paper concludes by summarizing key findings, highlighting the transformative role of OpenUSD in addressing ULDT implementation challenges, and proposing avenues for future research. This conclusive section serves as a reflection on the contributions made, guiding researchers and practitioners towards further advancements in the dynamic field of Urban Landscape Digital Twins.

Background and Related Work

At the genesis of Urban Landscape Digital Twins

The development of digital twins with a focus on urban management gained momentum around 2018, marking a notable progression in digital tools for urbanism. While digital twins are a recent advancement, the use of digital tools in urban planning dates to the 1950s, coinciding with the emergence of commercial computers. The Chicago Transportation Area Study in 1955 stands as a pioneering example of the first urban model, setting the stage for subsequent models aimed at aiding planning and policymaking, particularly focusing on the social aspects of cities [10]. Historical reviews, such as those by Boyce and Williams [11] on urban transportation modeling and Batty [12] on urban models in general, provide insights into the evolution of these models. Urban models initially addressed social aspects, including transportation [13-15], land-use and urban growth [16-19], and economic development [20-24]. Infrastructure models, dealing with systems like road infrastructure, water supply, sewage [26], and electric power transmission [27], evolved separately with distinct backgrounds and methodologies. Technical-oriented urban models showcased a diverse range of systems. 3D city models, despite early adoption, did not replace traditional city plans until the 2000s. The integration of Building Information Modeling (BIM) data [30-32] further refined these city models, linking digital representations of built assets. The 2010s witnessed the popularization of the smart city concept [36], emphasizing the collaboration between administration and citizens using new technologies to enhance efficiency, intelligence, sustainability, safety, inclusivity, and democracy. This era saw the sensitization of cities, yet pre-vailing approaches often lack the capability for direct interaction with the city itself [33-35].

Definition, Scope, and Lifecycle of ULDT

A DT, in the context of urban landscapes, refers to a highly detailed and dynamic virtual replica of a physical city or region. This comprehensive digital representation encompasses not only the spatial dimensions but also the temporal and functional aspects of the urban ecosystem. At its core, a ULDT is a digital mirror that emulates the physical reality of an urban environment. It extends beyond a static 3D model, integrating real-time data streams and historical information to create a living, breathing simulation of the cityscape. This simulation not only replicates the spatial arrangement of buildings, infrastructure, and natural elements but also models the intricate interactions between these components over time. The scope of ULDT spans across various domains, reflecting their versatility and utility.

Urban Planning and Development: Providing urban planners with a virtual sandbox to visualize and experiment with different scenarios. Facilitating data-driven decision-making in land-use planning, infrastructure development, and city expansion.

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Architectural Design: Enhancing the architectural design process by allowing architects to immerse themselves in a lifelike representation of the urban context. Supporting collaborative design efforts and enabling real-time adjustments based on the DT's feedback.

Infrastructure Management: Aiding in the monitoring and maintenance of critical urban infrastructure such as transportation systems, utilities, and public spaces. Predictive analytics for optimal maintenance scheduling and resource allocation.

Disaster Preparedness and Response: Serving as a tool for simulating and preparing for natural or man-made disasters. Facilitating emergency response planning and evaluating the potential impact of disasters on urban systems.

Community Engagement: Fostering community participation by providing an accessible platform for residents to understand and contribute to urban development. Enabling stakeholders to visualize the implications of proposed changes and express their opinions.

Expanding our focus to the city-scale and urban context, the lifecycle DT becomes notably more intricate and diverse [37]. Inherent to the nature of cities, the entire lifecycle involves multiple stages, encompassing the integration of heterogeneous information from inception to coevolution with the physical environment [38,39]. Moreover, the urban context introduces a dynamic dimension to the lifecycle [37], demanding reactive DT capable of incorporating near real-time representations of cities [40]. This necessitates the assimilation of a substantial volume of heterogeneous input data, feedback loops, and a high-frequency information flow throughout the lifecycle. For example, when encountering quality issues during model creation, revisiting previous stages becomes imperative for data re-acquisition. Examining the lifecycle of a 3D city model serves as an illustrative example [41,42]. Commencing with planning to define system architecture and practical value, the subsequent stages include acquisition, where approaches and techniques are determined, and data processing, involving the management of data complexity and adherence to standards. Dissemination pertains to visualization and interoperability, while application caters to diverse practical demands. Maintenance is crucial for detecting changes and updating the model. Inspired by the comprehensive lifecycle of 3D city models, integral to urban DT, we encapsulate the process into six phases as illustrated in Figure 1.

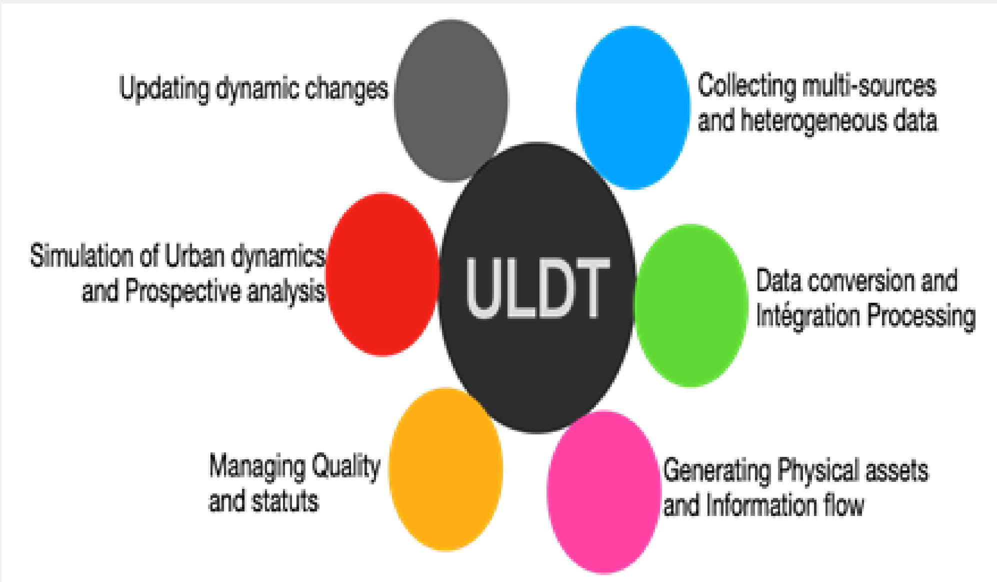

Figure 1: Lifecycle of Urban Landscape Digital Twin.

Urban Digital Twins Processing Technologies

Current urban DT processing is characterized by a sophisticated interplay of cutting-edge technologies that collectively redefine how we perceive, model, and interact with urban environments.

Geospatial Data Acquisition: In the realm of geospatial data acquisition, various technologies play pivotal roles in constructing detailed and accurate representations of urban landscapes. Photogrammetry [37], a technique that leverages aerial or ground-based imagery, emerges as a powerful tool for constructing three-dimensional models. By capturing imagery

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from different perspectives, photogrammetry enables the creation of highly detailed and realistic urban environments. Complementing photogrammetry is LiDAR, a technology that employs laser technology for precise mapping of urban topography [39]. By emitting laser beams and measuring their return times, LiDAR facilitates the generation of detailed elevation data, allowing for the creation of intricate 3D models that capture the fine nuances of urban terrain [25,30,33,38]. Satellite imagery contributes significantly to geospatial data acquisition by providing a bird's-eye view of urban areas. Utilizing satellite data for large-scale, high-resolution mapping enables comprehensive coverage, making it an invaluable resource for urban planners and researchers aiming to understand the macroscopic features and dynamics of urban landscapes.

Spatial Modeling and Simulation: Spatial modeling and simulation technologies are instrumental in understanding and predicting the complexities of urban environments. GIS (Geographic Information System) plays a central role in this domain by integrating spatial data to analyze and model various geographic phenomena. By overlaying different layers of information, GIS enables a holistic understanding of the spatial relationships within urban landscapes, aiding in effective decision-making. Building Information Modeling (BIM) takes spatial modeling to a granular level by creating detailed 3D models of buildings and infrastructure. This technology not only captures the physical dimensions of structures but also includes information about their components and systems. This level of detail [40,41] is crucial for architects, urban designers, and engineers in the planning and development phases. Agent-based modeling [42] introduces a dynamic dimension to spatial simulation by simulating individual agents, such as residents and vehicles, to model dynamic urban scenarios. This approach allows for the examination of emergent behaviors and interactions within urban systems, providing valuable insights into the social and functional aspects of urban landscapes.

Real-time Data Integration: Real-time data integration technologies are essential for keeping pace with the dynamic nature of urban environments. The Internet of Things (IoT) connects sensors and devices to collect real-time data on various urban parameters. From traffic flow to air quality, IoT contributes to a continuous stream of data that enhances the responsiveness of urban systems to changing conditions. Smart city [43] platforms further advance real-time data integration by aggregating data from diverse sources. These platforms serve as comprehensive hubs for urban monitoring, bringing together information from IoT devices, municipal databases, and other sources. This aggregation facilitates a holistic understanding of urban dynamics, enabling informed decision-making. Edge Computing addresses the need for real-time responsiveness by processing data closer to the source. By reducing latency and enhancing computational efficiency, edge computing ensures that critical decisions can be made in real-time, contributing to the overall effectiveness of urban systems.

Visualization and Interaction: Urban Digital Twins technologies excel in providing immersive visualization and interactive experiences. Augmented Reality (AR) and Virtual Reality (VR) technologies immerse stakeholders in lifelike urban environments [44]. These technologies allow users to visualize proposed changes, explore different scenarios, and assess the visual impact of urban interventions in a realistic and interactive manner. Interactive Dashboards [45-47] provide decision-makers with intuitive interfaces to explore and manipulate digital twin data. By presenting complex information in a user-friendly format, interactive dashboards empower urban planners and administrators to make data-driven decisions effectively. 3D Rendering Engines enhance the visual representation of urban landscapes by generating realistic images and animations. These engines contribute to creating visually compelling and accurate digital twins, fostering a deeper understanding of urban environments among stakeholders.

Materials and Methods

Rise of Technical Challenges in ULDT Implementation

We systematically reviewed numerous articles to discern the technical challenges associated with urban DT implementation. The analysis revealed a discernible upward trend in publications since 2017, indicating a growing emphasis on DT at the urban scale, with a concomitant exploration of their potentials and impediments. A meticulous scrutiny of the collected data enabled us to categorize all identified technical challenges into nine major categories, as delineated in Table 1. To enhance clarity and emphasize the current landscape of digital twin adoption in the urban and geospatial domains, Figure 2 vividly illustrates the severity of these challenges. The field of 3D data collection, storage, and management has matured, leading to increased utilization of 3D data. However, in urban contexts, there is a need for a comprehensive review to compare different 3D modeling methods and standards. This review would assess the efficacy, efficiency, and suitability of various approaches, provide valuable insights into advancements, and address evolving challenges. It would also guide future research and facilitate the adoption of standardized and effective 3D modeling techniques in urban domains. Contemporary 3D modeling approaches can be categorized into topological and geometric methods. Topological modeling methods focus on preserving relationships between geometries, while geometric modeling methods directly capture geographical coordinates. Integration of multiple modeling methods has gained popularity to address limitations and enhance efficiencies.

Scientific Advocacy for Open USD for ULDT Modeling

A diverse range of geospatial software and tools are available to facilitate 3D data models, performing functions such as viewing, generating, editing, converting, storing, parsing, and

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providing APIs for programmers. These tools play a crucial role, especially in organizational standards like CityGML, CityJSON, and IFC, and de facto standards like KML, SHP, DXF, COLLADA, and 3D PDF. However, the limitations of these existing standards and tools become evident when developing visual analytics systems for 3D geo simulation, as outlined in Table 2. Despite the significant potential of 3D modeling for spatial analysis in complex urban areas, the process remains time-consuming and labor-intensive. The absence of an internationally accepted data standard exacerbates format harmonization issues, emphasizing the need for fine-scale data, particularly in areas like ventilation animation and emergency management. Researchers in urban visual analytics and ULDT face challenges in determining suitable visualization techniques, computational methods, and the effective integration of visualization and computational models. Addressing these questions is pivotal for designing DT solutions for urban problems. The Open USD Ecosystem has been specifically designed to overcome these challenges and enhance urban DT by providing the capabilities detailed in Table 2. Leveraging Open USD can lead to more efficient and effective solutions in the realm of urban visual digitalizing and analytics.

Table 1: Challenges related to ULDT Implementation.

Challenge	Description of issues	Reference
Spatial Fidelity and Resolution	The limitation in spatial resolution and the ability to capture intricate spatial details within ULDT pose challenges in accurately representing the complex spatial structures and dynamics of urban areas. Many current models face challenges in accurately representing the spatial fidelity and resolution required to capture the intricate details of urban environments, leading to potential inaccuracies in the simulation outcomes.	[17, 20-22, 24, 25, 30-32]
Real-time Data Integration and Processing	The integration and processing of real-time data into ULDT models remains a challenge, impeding the development of dynamic and responsive frameworks for urban planning and management. Consequently, the ability to capture and simulate dynamic urban processes in a timely and accurate manner limited.	[13-15, 17, 19, 25, 33]
Modeling Complex Urban Dynamics	Effectively modeling and simulating the multifaceted interactions among various urban elements, such as buildings, infrastructure, and human activities, remains a complex challenge for ULDT. Current models often struggle to effectively capture and simulate the complex spatial interactions and dynamics among various urban elements, such as buildings, infrastructure, and human activities, leading to a limited understanding of the holistic urban environment.	[14-16, 22, 30, 36, 40]
Data Fusion and Integration	The seamless integration and fusion of diverse data sources, including remote sensing data, geographical information, and real-time sensor data, present challenges in creating comprehensive and holistic representations of urban environments in ULDT, leading to potential inconsistencies and limitations in the simulation outcomes.	[36, 37, 40, 41, 45, 46]
Accuracy and Reliability of Simulation Outcomes	Ensuring the accuracy and reliability of simulation outcomes in geo simulation models, particularly when considering complex and dynamic urban processes, remains a critical challenge for researchers and practitioners.	[26, 27, 45, 47-49, 50]
Lack of Standardisation	The absence of standardized data formats and visualization methods among diverse cities and organizations presents a barrier to seamless integration and comparison of urban data. This deficiency limits interoperability and data exchange, thereby posing challenges to the realization of effective visual analytics on a broader scale.	[36, 37, 40, 45, 46, 48]
Restricted Semantic Enrichment	The infusion of contextual information via semantic enrichment is pivotal for urban visual analytics. Nevertheless, current standards encounter challenges in articulating intricate urban features, impeding the thorough capture and analysis of urban phenomena and impeding the advancement of urban visual analytics.	[22, 36, 37, 40, 41, 45]
Scalability and Efficiency	With the expansion of urban datasets in both size and complexity, effective data processing and visualization techniques become indispensable for optimal performance. Current standards may fall short in meeting scalability demands, resulting in slower analysis and rendering speeds. This constraint can impede real-time and interactive urban visual analytics, particularly concerning extensive datasets.	[36, 42, 43]
Human-Centric Design Approach	Although standards offer a foundation for data representation and visualization, they might not fully address the varied needs and preferences of diverse user groups, such as urban planners, policymakers, and researchers. The customization and adaptability of visual analytics tools to accommodate specific user requirements are imperative for effective analysis and decision-making.	[28, 36, 40, 41, 43, 44]

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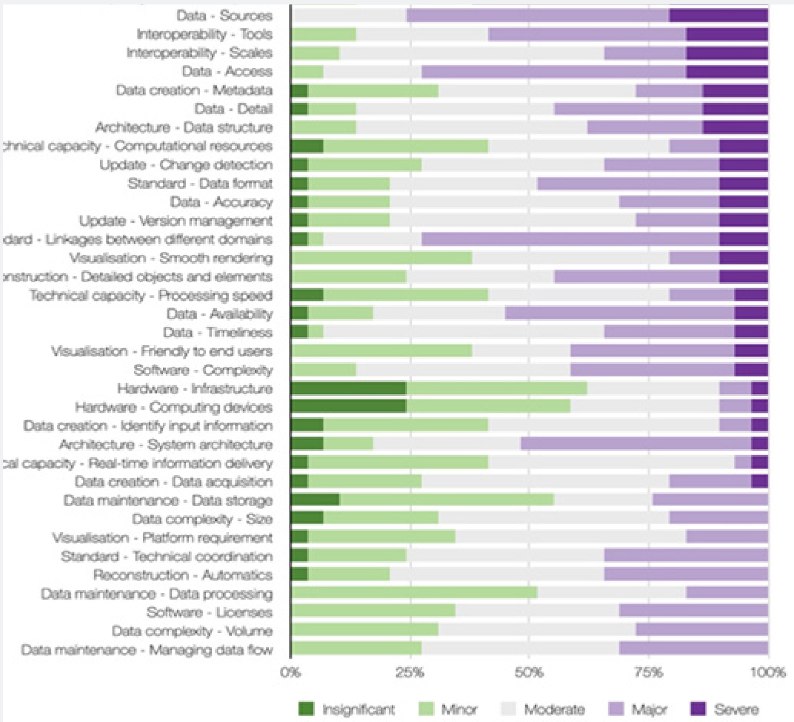

Figure 2: Lifecycle of Urban Landscape Digital Twin.

Table 2: Evolving vision of usual international 3D format standards: The strength of Open USD.

Comparison criteria	DXF	SHP	VRML	X3D	KML	Collada	IFC	CityGML	CityJSON	Open USD
3D Geometry	++	+	++	+	+	++	++	++	++	++
Topology	-	-	0	0	-	+	+	+	++	++
Texture	-	0	++	++	0	++	-	+	-	++
Semantics	+	+	0	0	0	0	++	++	++	++
Attributes	-	+	0	0	0	-	+	+	++	++
Augmented reality	-	-	0	0	-	0	0	0	+	++
LoD	-	-	+	+	-	-	-	+	+	++
JSON	-	-	-	-	-	-	-	0	++	++
Georeferencing	+	+	-	+	+	-	-	+	++	++
Legend: Unsupported (-), Basic support (0), Supported (+), Extended support (++)										

Methodology for Urban 3D Visual Features Digitalizing

This section delineates the procedures and methdologies applied in the acquisition, processing, modeling, and implementing ULDT for urban geo simulation. Figure 3 presents the methodological summary. This workflow of ULDT implementation details a sequential series of steps and methodologies utilized for the acquisition, processing, modeling, and simulation of urban visual features. It spans data collection, pre-processing, geometry modeling, modeling of visual features, the incorporation of USD standard specifications for organization, and the integration of geo simulation techniques within the USD framework. This holistic approach is designed to guarantee the generation of precise and realistic urban 3D models that are well-suited for geo simulation applications.

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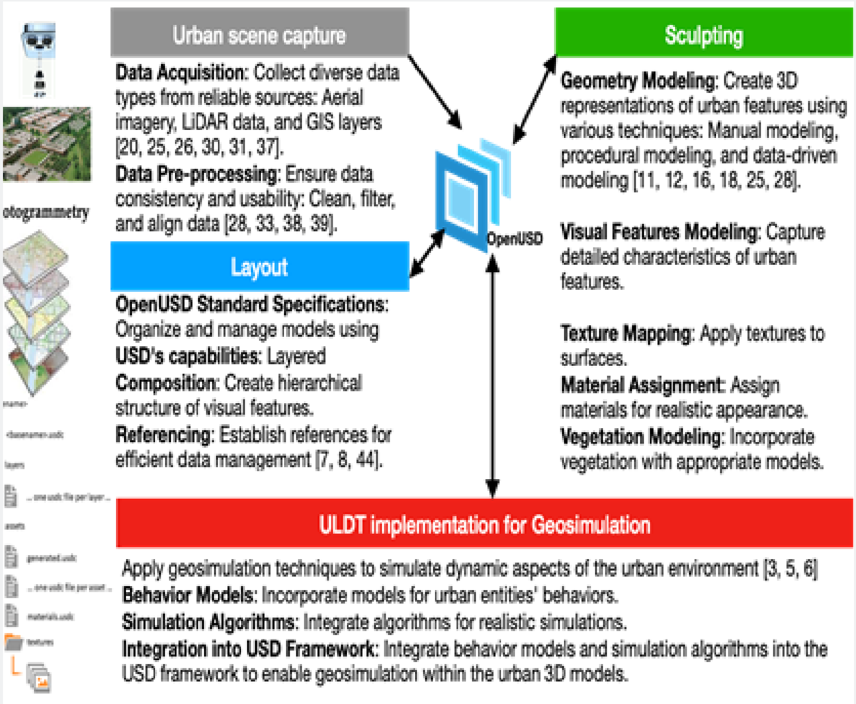

Figure 3: ULDT Implementation Methodology.

Experimental Real Application

Experimental Urban Area: In this experimental instantiation of ULDT, we applied the stipulated methodological workflow to a segment of the recently developed residential enclave known as “Jardins du MONT” in Belfort, France (Figure 4). This housing project comprises 25 plots with individual houses, each ranging from 600 to 900 m2. “Jardins du MONT” stands out as a contemporary development distinguished by its high-quality architectural design. Strategically positioned, it lies within a 10-minute commuting distance from Belfort’s city center, accessible by car, bus, or bike. Additionally, it enjoys proximity to the vibrant “Techn’Hom” business park, home to major companies like GE and Alstom. This strategically advantageous location provides residents with a serene and verdant urban environment, offering breathtaking views of Belfort and its fortifications. The primary thrust of our research in this study revolves around 3D spatial analysis, the temporal evolution of new housing estates, and the pragmatic implementation of smart city concepts through the utilization of advanced tools in artificial intelligence. Given the dynamic nature of the ongoing development in this urban area, the deployment of our ULDT was considered indispensable for conducting a forward-looking analysis of the evolving urban built environment.

Experimental settings: In the realm of modeling visual features for ULDT and 3D geo simulation, the USD standard schema emerges as a resilient and adaptable framework for representing 3D scenes and assets. Its layered composition and referencing capabilities provide an effective means for organizing and managing intricate urban scenes. Offering a flexible and scalable framework, the schema aptly captures the geometry, attributes, relationships, and behaviors of objects within a scene. Utilizing a combination of JSON and binary formats, it ensures the efficient storage and transmission of 3D data.

Through its incorporation of geometry, attributes, and metadata, the schema enables precise and detailed descriptions of visual features in files. Essentially, USD files encapsulate data that defines the appearance of a scene, interpreted by rendering applications to generate images on the screen. To assess the efficacy of the proposed approach leveraging USD standard specifications, a series of experiments were conducted to craft the digital twin of a housing estate [1]. These experiments utilized a representative dataset of the urban environment, as depicted in Figure 5. In catering to the diverse visual characteristics of various urban residences, including houses, apartments, and other dwellings, a comprehensive database was meticulously curated. This database, integral to our algorithmic developments, comprises 800 photos capturing a hundred distinct houses. Rigorous adherence to overlap constraints was maintained during the data collection process to ensure the robustness of

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our algorithms. The database is curated with 799 calibrated image pairs, meticulously organized based on stereovision image matching constraints. The experiments encompass four distinct categories, detailed in Table 3.

Figure 4: Experimental Urban Area “Jardins du MONT”, Belfort (France).

Figure 5: Dataset sample for ULDT implementation with the USD schema.

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Table 3: OpenUSD-Based ULDT modeling process experimental phases.

Experiments	Description
Layered Composition and Referencing Evaluation	Assessing the effectiveness of layered composition and referencing in urban visual feature modeling. A simplified urban scene was created with multiple layers for buildings, roads, vegetation, and terrain. Layer referencing and overrides were used to establish dependencies and customize the model. The experiment evaluated the efficiency, flexibility, and user-friendliness of the layered composition and referencing features.
Geometry Modeling and Material Assignment	Focus on assessing the accuracy and visual quality of geometry modeling and material assignment. Detailed 3D models of buildings, roads, and vegetation were created using USD-supported geometric representations. Material properties like color, reflectivity, and texture mapping were assigned to enhance visual realism. The experiment involved visual inspections and comparisons with reference data to evaluate the fidelity of the models.
Integration and Simulation	Integration of urban visual feature models into a 3D geosimulation framework. Testing with different simulation scenarios, including urban planning, traffic simulation, and environmental analysis. The goal was to evaluate the performance, accuracy, and interactivity of the model in simulating and analyzing the urban environment.
Validation and Comparison	The final experiment involved validating the proposed approach by comparing the results with existing methods for urban built environment visual feature modeling. A comparative analysis was performed on various metrics, including computational efficiency, model accuracy, and ease of use. The experiment aimed to demonstrate the advantages and improvements offered by the proposed approach using USD standard specifications.

Experimental Results Analysis: Our investigation aimed to assess the effectiveness, precision, and efficiency of the urban visual feature modeling process, with a comparative analysis against prevailing methods in urban simulation and analysis. In the initial experiment, the hierarchical organization facilitated by USD demonstrated its prowess in modular development and management of the urban environment, showcasing the capability to establish layer dependencies.

This emphasized the adapt-ability and user-friendliness of layered composition and referencing, enabling the seamless creation of intricate and realistic urban scenes. The second experiment focused on evaluating the accuracy and visual quality of the geometry modeling and material assignment process. Results indicated that USD provided a robust framework for crafting detailed and realistic 3D models of urban features. Supported geometric representations, including polygons, NURBS curves, and surfaces, allowed for precise shape and structure representation. Material and texture assignments further enhanced the visual realism of the models. In essence, this experiment affirmed that the proposed approach using USD standard specifications yielded high-fidelity urban visual feature models. Moving on, the third experiment delved into the integration of urban visual feature models into a 3D geo simulation framework and subsequent assessment of simulation results. The integrated model successfully simulated diverse scenarios, spanning urban planning, traffic simulation, and environmental analysis. Evaluation of the model's performance in terms of computational efficiency and accuracy showcased real-time interactivity, empowering researchers to dynamically explore and analyze the urban environment. This experiment underscored the suitability of the proposed approach for comprehensive 3D geo simulation applications. In the fourth experiment, our approach was validated and compared against existing methods for modeling urban built environment visual features. Metrics such as computational efficiency, model accuracy, and ease of use were considered. Results indicated that the proposed approach using USD standard specifications outperformed traditional methods in terms of efficiency and flexibility. The iterative refinement capability through layer referencing and overrides significantly reduced manual rework, enhancing overall productivity. For a concise overview of performance and improvements, refer to Table 4.

Table 4: USD' s metrics compared to current standards for Urban Visual features modeling.

Metric	X3D	IFC	CityGML/CityJSON	USD
Computational efficiency	Low	Moderate	Moderate	Higher
Model accuracy	Comparable	Comparable	Comparable	Comparable
Ease of use	Moderate	Moderate	Moderate	User-friendly
Manual rework	Higher	Moderate	Higher	Reduced
Productivity	Low	Moderate	Moderate	Improved
Flexibility	Low	Moderate	Low	Higher

Conclusion and Future Work

This paper has delved into the intricate realm of Urban Landscape Digital Twin (ULDT) implementation challenges and proposed effective solutions anchored in the Open USD ecosystem. Through a meticulous exploration of historical developments, conceptual frameworks, and contemporary Urban Digital Twins

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processing technologies, we identified and addressed critical challenges such as data integration, scalability, interoperability, and security. The advocacy for Open USD as a solution has been substantiated by its open-source nature, standardized approach, and commendable capabilities in handling large-scale 3D models with high fidelity. The experimental application of Open USD in a real urban environment showcased promising results, providing tangible evidence of its transformative potential in overcoming the identified challenges. Looking ahead, the future of ULDT research and application presents exciting prospects and avenues for exploration. One paramount aspect involves further refining and expanding the Open USD ecosystem to accommodate evolving urban landscapes and technological advancements. Collaborative efforts within the research community can contribute to enhancing Open USD's capabilities and addressing emerging challenges. Additionally, the integration of artificial intelligence and machine learning techniques holds promise in optimizing ULDT workflows, automating data processing, and enriching the predictive capabilities of DT.

The practical implications of ULDT in urban planning and development warrant continued investigation. Further case studies and real-world applications can deepen our understanding of Open USD's effectiveness in diverse urban contexts and contribute to the development of best practices for its implementation. As the field progresses, fostering interdisciplinary collaborations among urban planners, architects, data scientists, and technologists becomes pivotal for leveraging the full potential of ULDT and Open USD. In the realm of policy and governance, the adoption of standards for ULDT implementation is crucial. Establishing guidelines for data privacy, security, and ethical considerations ensures responsible and transparent deployment of digital twin technologies in urban environments. Furthermore, engaging with city stakeholders, including residents and businesses, in the co-creation of digital twins fosters a sense of ownership and collective responsibility for the sustainable development of urban areas. Our paper not only addresses the immediate challenges of ULDT implementation but also lays the foundation for a future where Open USD and similar technologies redefine how we plan, design, and manage our urban spaces. Through continued research, collaboration, and technological innovation, we embark on a journey towards more resilient, efficient, and sustainable urban landscapes.

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