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Multi-Scalar Urban Digital Twin Design: Architecture and OpenUSD Standards Based Methodology

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Abstract

Digital twins have become indispensable tools in urban planning, providing dynamic and interactive portrayals of urban landscapes. This paper presents an innovative perspective on urban digital twin design, placing a pronounced emphasis on a multi-scalar framework that captures the intricate dynamics of urban systems across macro, meso, and micro scales, enriched by the concept of varying levels of detail. The proposed architectural model is rooted in OpenUSD standards, harnessing the Universal Scene Description format to amplify interoperability, facilitate seamless data exchange, and enable nuanced capture of urban visual features. Our exhaustive methodology addresses the constraints observed in existing urban digital twin frameworks and showcases the effectiveness of our approach through practical implementation in real-world urban settings. The outcomes underscore the critical role of multi-scalar representation and the integration of OpenUSD standards in propelling the capabilities of urban digital twins, thereby fostering more enlightened and responsive urban planning.

Keywords: Urban digital twin; Multi-Scale representation; OpenUSD standards; Urban planning; Level of detail; Urban visual features

Introduction

In the contemporary complex tapestry of urban landscapes, the intricate interplay of diverse systems, structures, and scales presents some scientific challenges for urban planning. As cities evolve at an unprecedented pace, the demand for innovative methodologies to comprehend, model, and manage their dynamic complexities has never been more pressing. Within this context, the concept of Urban Digital Twins (UDT) has emerged as a transformative paradigm, offering a holistic and real-time representation of urban environments. The roots of the Digital Twin (DT) philosophy can be traced back to the 1960s, notably employed by the National Aeronautics and Space Administration (NASA). Michael Grieves played a pivotal role in definitively consolidating the concept in 2003 [1, 2]. Grieves articulated that a DT model comprises three fundamental elements: the physical assets, a virtual model, and the intricate network of data and information that establishes crucial linkages between the virtual and real domains. Beyond being static representations, DTs have evolved into dynamic counterparts with the ability to emulate, forecast, optimize, and control the physical landscape through sophisticated real-time connectivity, mapping, analysis, and interaction. This paper introduces a novel perspective on Multi-Scalar Urban Digital Twin (MSUDT) design, emphasizing the need for a comprehensive architecture capable of capturing the intricacies of urban systems across varying scales. The challenges in existing frameworks are addressed through the integration of OpenUSD standards, a robust and versatile technology rooted in the Universal Scene Description (USD) format. OpenUSD not only facilitates enhanced interoperability and data exchange but also provides a means to capture urban visual features with fidelity. Navigating the complexities of contemporary urban planning requires a shift from conventional digital twin approaches to a multi-scalar framework that encapsulates the hierarchical nature of urban systems. This exploration extends beyond theoretical frameworks to the pragmatic application of these digital twins in urban planning, architecture, and engineering. A focal point of this investigation is the examination of the OpenUSD ecosystem as a pivotal solution to the multifaceted challenges inherent in the implementation of Multi-Scalar Urban Digital Twins. 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 UDT, particularly regarding the multi-scale issue. Indeed, when it comes to urban planning and development, the demand 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. OpenUSD, 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 adaptability to handle large-scale urban models with high geometric and visual fidelity positions it as a transformative tool for advancing the capabilities of urban digital twins. The structure of this paper is designed to provide a cohesive and comprehensive exploration of the key elements surrounding (MSUDT) design. It unfolds from the foundational concepts and challenges to the proposed architecture and the instrumental role of OpenUSD in shaping the future of urban planning through advanced digital twin methodologies. The Literature Review section of this paper aims to establish the foundation for Multi-Scalar Urban Digital Twin (MSUDT) design by synthesizing existing knowledge on digital twins, urban planning, and the challenges associated with representing urban environments at multiple scales. The review will delve into the historical evolution of digital twin concepts, emphasizing key milestones and influential works that have shaped the discourse. In section 3, we provide a detailed exposition of the approach taken to design the Multi-Scalar Urban Digital Twin and the methodology employed for its implementation. This will include a thorough discussion of the data sources utilized, such as geospatial data, building information models (BIM), and other relevant datasets. The integration of OpenUSD standards within the methodology will be elaborated upon, highlighting how the Universal Scene Description format is leveraged for enhanced interoperability, data exchange, and the representation of urban visual features. The section will emphasize the rationale behind the chosen methods, the tools employed, and the step-by-step procedures involved in creating the MSUDT architecture.

The integration of OpenUSD standards within the architecture will be highlighted in section 4. In Section 5, we meticulously delineate the parameters of our experiments, elucidating the specific settings, configurations, and data sources meticulously employed in implementing OpenUSD for MSUDT modeling and design. This meticulous exposition aims to ensure transparency and reproducibility, offering invaluable insights for future researchers and practitioners embarking on similar applications. The paper culminates by synthesizing key findings, underscoring the transformative role of OpenUSD in mitigating challenges associated with MSUDT implementation. In doing so, it provides a critical reflection on the contributions made throughout the research. This concluding section not only consolidates the outcomes of our endeavors but also serves as a guiding beacon for researchers and practitioners, directing them towards the frontier of possibilities in the everevolving realm of Urban Digital Twin technology.

Literature Review

Advancements in 3D Urban Modeling and Digital Twins

The domain of 3D data collection, storage, and management has reached a level of maturity, resulting in the widespread utilization of 3D data [30]. Nevertheless, the urban context necessitates a comprehensive exploration to compare diverse 3D modeling methods and standards. This scrutiny aims to evaluate the effectiveness, efficiency, and appropriateness of various approaches, offering valuable insights into progress and addressing emerging challenges. Furthermore, it serves as a guiding resource for future research, fostering the adoption of standardized and efficient 3D modeling techniques in urban domains.

The evolution of digital twins, with a specific focus on urban management, gained substantial traction around 2018, marking a significant leap in digital tools for urban planning. While the concept of digital twins is relatively recent, the use of digital tools in urban planning traces its roots back to the 1950s, coinciding with the advent of commercial computers. A seminal example is the Chicago Transportation Area Study in 1955, representing the inaugural urban model and laying the foundation for subsequent models aimed at aiding planning and policymaking, particularly emphasizing the social aspects of cities [10]. Historical reviews, including works by Boyce and Williams [11] on urban transportation modeling and Batty [12] on urban models in general, provide invaluable insights into the evolution of these models.

Initially centered on social aspects such as transportation [13-15], land-use, and urban growth [16-19], and economic development [20-24], urban models diversified over time. Infrastructure models, dealing with systems like road infrastructure [24, 25], water supply, sewage [26], and electric power transmission [27], developed independently with distinctive backgrounds and methodologies. Technical-oriented urban models encompassed a spectrum of systems. Despite early adoption, 3D city models did not supersede traditional city plans until the 2000s [28, 29]. The integration of Building Information Modeling (BIM) data [30-32] further refined these city models by linking digital representations of built assets.

The 2010s witnessed the popularization of the smart city concept [36], emphasizing collaboration between administration and citizens using new technologies to enhance efficiency, intelligence, sustainability, safety, inclusivity, and democracy. This period saw the sensorization of cities, yet prevailing approaches often lack the capability for direct interaction with the city itself [33-35].

Urban Digital Twin: A Comprehensive Overview and Lifecycle

In the realm of urban landscapes, a Digital Twin (DT) takes the form of a highly intricate and dynamic virtual replica of a physical city or region. This digital representation transcends the spatial dimensions, encompassing both temporal and functional aspects of the urban ecosystem. Essentially, an UDT serves as a digital mirror, faithfully mirroring the physical reality of an urban built environment. It goes beyond the static confines of a 3D model by integrating real-time data streams and historical information, thereby creating a vibrant and continuously evolving simulation of the cityscape. This simulation not only captures the static arrangement of buildings, infrastructure, and natural elements but also models the intricate interactions between these components over time. The scope of UDT is expansive, reflecting its versatility and applicability across various domains.

Urban Planning and Development: It serves as a virtual sandbox for urban planners, offering a platform to visualize and experiment with different scenarios. This facilitates data-driven decision-making in crucial aspects such as land-use planning, infrastructure development, and city expansion.

Architectural Design: UDT enhances the architectural design process by immersing architects in a lifelike representation of the urban context. It supports collaborative design efforts and enables real-time adjustments based on feedback from the DT.

Infrastructure Management: It aids in the monitoring and maintenance of critical urban infrastructure, including transportation systems, utilities, and public spaces. Predictive analytics embedded in UDT assist in optimal maintenance scheduling and resource allocation.

Disaster Preparedness and Response: UDT functions as a tool for simulating and preparing for natural or man-made disasters. It plays a crucial role in emergency response planning by evaluating the potential impact of disasters on urban systems.

Community Engagement: By providing an accessible platform, UDT fosters community participation in understanding and contributing to urban development. It empowers stakeholders to visualize the implications of proposed changes and express their opinions.

As we expand our focus to the city-scale and urban context, the lifecycle of DT becomes notably intricate and diverse [37]. Reflecting the inherent complexity 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 a 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 reacquisition. 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.

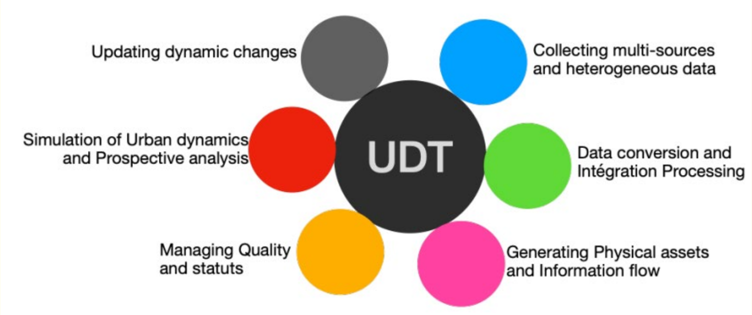


Figure 1: Lifecycle of Urban Digital Twin.

Technology Holistic Perspective and Scale Issues

The contemporary landscape of UDT processing is marked by a sophisticated interplay of cutting-edge technologies that redefine our perception, modeling strategies, and interaction paradigms within urban environments.

Geospatial Data Acquisition: In the realm of geospatial data acquisition, a con-vergence of technologies reshapes our approach to constructing detailed and accurate representations of urban landscapes. Photogrammetry [37], leveraging aerial or ground-based imagery, stands out as a powerful tool for constructing three-dimensional models. By capturing imagery from diverse perspectives, photogrammetry enables the creation of highly detailed and realistic urban environments. LiDAR, utilizing laser technology for precise mapping of urban topography [39], complements photogrammetry. Satellite imagery, offering a bird's-eye view of urban areas, contributes significantly to large-scale, high-resolution mapping, proving invaluable for urban planners and researchers.

Spatial Modeling and Simulation: Spatial modeling and simulation technologies play a pivotal role in understanding and predicting the complexities of urban environments. GIS (Geographic Information System) integrates spatial data to analyze and model various geographic phenomena, offering a holistic understanding of spatial relationships. BIM takes spatial modeling to a granular level by creating detailed 3D models of buildings and infrastructure [26, 29, 33]. Agent-based modeling [42] introduces a dynamic dimension by simulating individual agents, allowing examination of emergent behaviors within urban systems.

Real-time Data Integration: Real-time data integration technologies are paramount 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. Smart city platforms aggregate data from diverse sources, serving as comprehensive hubs for urban monitoring. Edge Computing, by processing data closer to the source, reduces latency and enhances computational efficiency for real-time decision-making.

Visualization and Interaction: Urban Digital Twins excel in providing immersive visualization and interactive experiences. Augmented Reality (AR) and Virtual Reality (VR) technologies immerse stakeholders in lifelike urban environments [44], allowing visualization of proposed changes and exploration of different scenarios. Interactive Dashboards [45-47] provide decision-makers with intuitive interfaces to explore and manipulate digital twin data, empowering effective, data-driven decision-making.

Scale Issues and Emerging Trends: In the face of multi-scale, multi-scenario, multi-dimensional applications of UDT, termed here as MSUDT, complexities arise in modeling entire urban elements, processes, and complexities simultaneously. Achieving full-scale modeling from macro to micro compositions is challenging, given current limitations in modeling levels and computing power. Scholars are exploring new standard methods for modeling complex digital twins for multi-scale, multi-context applications. Various proposed approaches, such as Modularity-Autonomy-Connectivity-Digital Twin [48] and hierarchical multi-granularity digital twin [49], aim to enhance perceptions and control in different layers [50]. However, challenges remain in defining interfaces and development processes for these complex digital twins. 3D rendering engines contribute to the visual representation of urban land-scapes by generating realistic images and animations, thereby enhancing the under-standing of urban environments among stakeholders.

Materials and Methods

Technical Hurdles Consideration in Implementing Urban Digital Twins

As the utilization of information technology continues to evolve, the pressing question emerges: how can we effectively integrate, interact, expand, and reuse the modeling of DT for urban built environments? The advent of information technology has not only opened doors to innovative services but has also catalyzed a systematic review of numerous articles, dissecting the technical challenges entwined with UDT implementation. Our analytical journey, a meticulous review of publications, unraveled a discernible upward trend since 2017, underscoring the growing significance of DT at varying urban scales. This surge in interest is coupled with an exploration of their potentials and the hurdles they encounter. A thorough examination of the amassed data empowered us to categorize the identified technical challenges into nine distinct categories, as meticulously outlined in Table 1. For a clearer depiction of the current landscape of DT adoption in urban and geospatial domains, Figure 2 vividly illustrates the severity of these challenges.

Challenge	***Description of issues***	***References***
Spatial Fidelity and Resolution	The limitation in spatial resolution and the ability to capture intricate spatial details within UDT pose challenges in accurately representing the complex spatial structures and dynamics of urban. 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 UDT models remain 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 is 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 UDT. 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 UDT, 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 geosimulation 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 Standardization	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]

Table 1: UDT Implementation Challenges to Consider Throughout the Design Process.

The field of 3D data collection, storage, and management has undergone maturation, witnessing an increased reliance on 3D data. However, when applied in urban contexts, a critical need arises for a comprehensive review that scrutinizes and compares different 3D modeling methods and standards. Such a review not only evaluates the efficacy, efficiency, and suitability of diverse approaches but also imparts valuable insights into technological advancements and confronts the ever-evolving challenges. Contemporary 3D modeling approaches can be broadly classified into topological and geometric methods. Topological modeling methods are designed to preserve relationships between geometries, ensuring the integrity of spatial connections. In contrast, geometric modeling methods directly capture geographical coordinates, providing a more direct representation of physical space. A noteworthy trend in contemporary practices involves the integration of multiple modeling methods, a strategic response to address limitations and enhance overall modeling efficiencies. This comprehensive review aims not only to delineate the current state of UDT implementation challenges but also to guide future research endeavors. By identifying and categorizing these challenges, our work serves as a roadmap for the adoption of standardized and effective 3D modeling techniques within urban domains.

Requirements and Scientific Advocacy for OpenUSD

In the context of modeling visual aspects of the urban built environment for 3D geosimulation within a UDT framework, the OpenUSD standard schema emerges as a resilient and versatile framework for representing 3D scenes and assets. Its layered composition and referencing functionalities significantly contribute to the organization and management of intricate urban scenes [4, 28, 32, 37, 38, 44, 50-53]. This schema offers a flexible and scalable structure for delineating the geometry, attributes, relationships, and behaviors of objects within a scene. Utilizing a blend of JSON and binary formats ensures the efficient storage and transmission of 3D data. By encapsulating geometry, attributes, and metadata, it enables precise and detailed descriptions of visual features in files. Essentially, USD files contain data that instructs rendering applications on generating images on the screen. There are various types of USD files. Readable ASCII text files, denoted by the *.usda* extension, provide human-readable representations. For a more compact and efficient binary representation, the *.usdc* extension format is employed. Additionally, USD supports a packaging format, indicated by the.usdz extension, which consolidates multiple USD files and associated auxiliary files (e.g., textures) within an uncompressed zip archive.

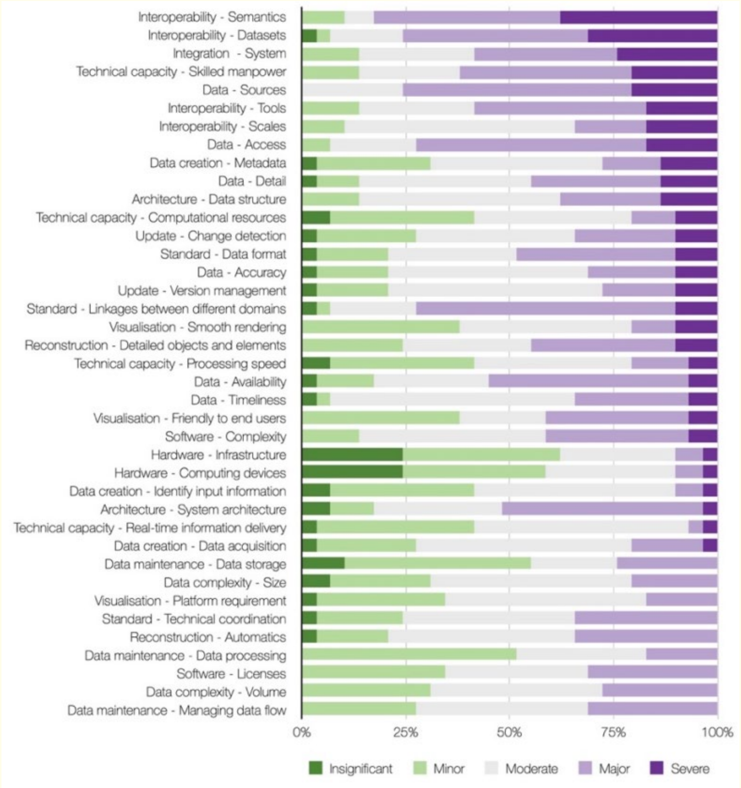


Figure 2: UDT Implementation Challenges Rating by Severity.

Comparison criteria	***DXF***	***SHP***	***VRML***	***X3D***	***KML***	***Collada***	***IFC***	***CityGML***	***CityJSON***	***OpenUSD***
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 (++)										

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

The comprehension and utilization of USD in urban visual modeling hinge on essential concepts. Geometry representation involves primitives such as polygons, NURBS, curves, and points, facilitating accurate depictions of urban elements. Instancing supports the efficient rendering of repetitive objects. A stage acts as a hierarchical structure organizing graphical information, comprising layers containing scene elements. Prims, serving as primary container objects, establish a hierarchy within the stage. Schemas define the interpretation of prim types using structured data. JSON and binary formats specify schemas for efficient storage and transmission. Prims possess attributes with types and values, allowing for default values and metadata. Attributes, prims, and stages can contain metadata for additional information. This flexibility enables the specification of material properties, environmental conditions, and other annotations for urban visual features.

A diverse array of geospatial software and tools plays a crucial role in supporting various functions related to 3D data models. These functions encompass viewing, generating, editing, converting, storing, parsing, and providing APIs for programmers. The significance of these tools is particularly pronounced in organizational standards like CityGML, CityJSON, and IFC, as well as de facto standards like KML, SHP, DXF, COLLADA, and 3D PDF. However, the limitations of these existing standards and tools become apparent when developing visual analytics systems for 3D geosimulation, as detailed in Table 2.

Despite the substantial potential of 3D modeling for spatial analysis in complex urban areas, the process remains time-consuming and laborintensive. The lack of a globally accepted data standard exacerbates format harmonization issues, especially in domains like ventilation animation and emergency management that require fine-scale data. Researchers in urban visual analytics and UDT encounter 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. Leveraging OpenUSD can lead to more efficient and effective solutions in the realm of urban visual digitalization and analytics via MSUDT model.

Methodology for MSUDT Architecture Design and Implementation

Constructing a Multi-Scalar Urban Digital Twin (MSUDT) is inherently challenging due to the diverse scales and contexts inherent in a complex urban system. Recognizing the intricate nature of cities, a modeling methodology based on a division-assemble architecture is proposed, as depicted in Figure 3. Semeraro et al. [53] under-score the complexity of systems, noting that they span various scales from fine details to large-scale systems, and further diversify across different scenarios in primary application contexts. To address this complexity, the MSUDT is logically divided according to spatial scales. This division implies that the lowest layer of the system should be implementable using existing technology, with OpenUSD being the technological cornerstone in this research. To facilitate the reusability of DT models, generic functions or services of DT are encapsulated as components. Given that software serves as the ultimate carrier of DT, the lowest level of a complex system is represented by the code layer used to develop these encapsulated components. Building upon this foundation, we introduce a Code-Component-Context-Composition architecture for the division of the MSUDT, as illustrated in Figure 3. The Composition aspect divides the MSUDT into different scales (layers), where Context represents the specific application scenario, Component signifies the functional unit for constructing simple digital twins, and Code represents the specific implementation of these components.

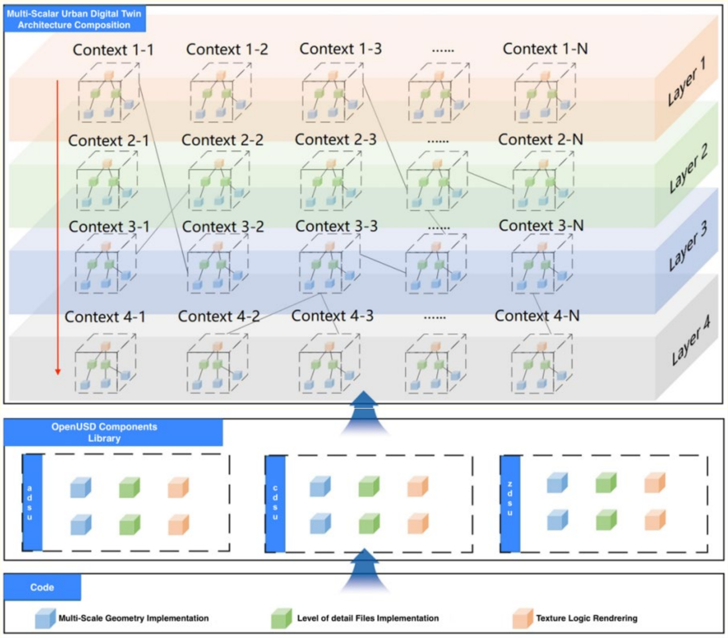
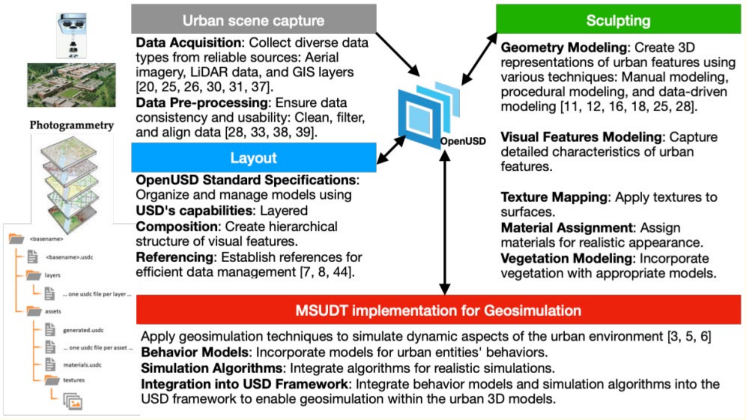


Figure 3: MSUDT Architecture Design.

Figure 4 provides a comprehensive overview of the proposed methodology. It outlines the procedures and methodologies employed in the acquisition, processing, modeling, and implementation of MSUDT for urban geosimulation and prospective analysis. The MSUDT implementation workflow details a sequential series of steps and methodologies applied to the acquisition, processing, modeling, and simulation of urban visual features. This includes data collection, preprocessing, geometry modeling, modeling of visual features, the incorporation of USD standard specifications for organization, and the integration of geosimulation techniques within the USD framework. This holistic approach is meticulously designed to ensure the generation of precise and realistic urban 3D models that are well-suited for geosimulation applications.



Urban scene capture

Data Acquisition: Collect diverse data types from reliable sources: Aerial imagery, LiDAR data, and GIS layers [20, 25, 26, 30, 31, 37].
Data Pre-processing: Ensure data consistency and usability: Clean, filter, and align data [28, 33, 38, 39].

Layout

OpenUSD Standard Specifications: Organize and manage models using
USD's capabilities: Layered
Composition: Create hierarchical structure of visual features.
Referencing: Establish references for efficient data management [7, 8, 44].

Sculpting

Geometry Modeling: Create 3D representations of urban features using various techniques: Manual modeling, procedural modeling, and data-driven modeling [11, 12, 16, 18, 25, 28].

Visual Features Modeling: Capture detailed characteristics of urban features.

Texture Mapping: Apply textures to surfaces.
Material Assignment: Assign materials for realistic appearance.
Vegetation Modeling: Incorporate vegetation with appropriate models.

MSUDT implementation for Geosimulation

Apply geosimulation techniques to simulate dynamic aspects of the urban environment [3, 5, 6]
Behavior Models: Incorporate models for urban entities' behaviors.
Simulation Algorithms: Integrate algorithms for realistic simulations.
Integration into USD Framework: Integrate behavior models and simulation algorithms into the USD framework to enable geosimulation within the urban 3D models.

Figure 4: MSUDT Implementation Methodology Workflow.

Experimental Real Application

Experimental Instantiation Area

In this experimental instantiation of the MSUDT, we meticulously applied the prescribed methodological workflow to a segment of the recently developed residential enclave known as "Jardins du MONT" in Belfort, France (refer to Figure 5). This housing project comprises 25 plots, each featuring individual houses ranging from 600 to 900 m2. "Jardins du MONT" stands as a contemporary development distinguished by its high-quality architectural design. Situated strategically, it boasts a convenient 10-minute commuting distance from Belfort's city center, accessible by car, bus, or bike. Furthermore, its proximity to the vibrant "Techn'Hom" business park, housing major companies like GE and Alstom, adds to its appeal. This strategically advantageous location not only provides residents with a serene and verdant urban environment but also offers breathtaking views of Belfort and its fortifications. The focal point of our research in this study revolves around three-dimensional 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 MSUDT was deemed indispensable for conducting a forward-looking analysis of the evolving urban built environment.

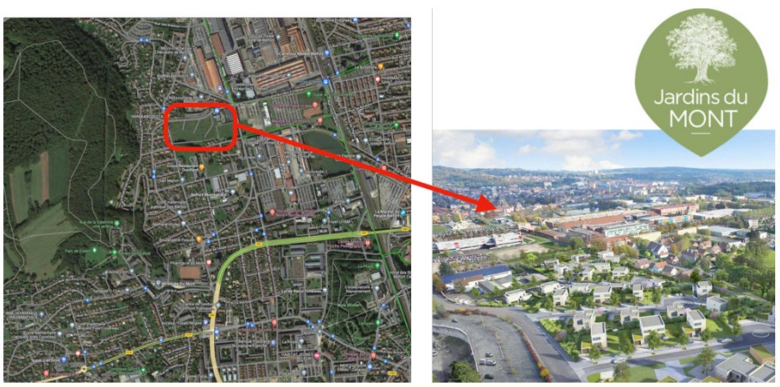
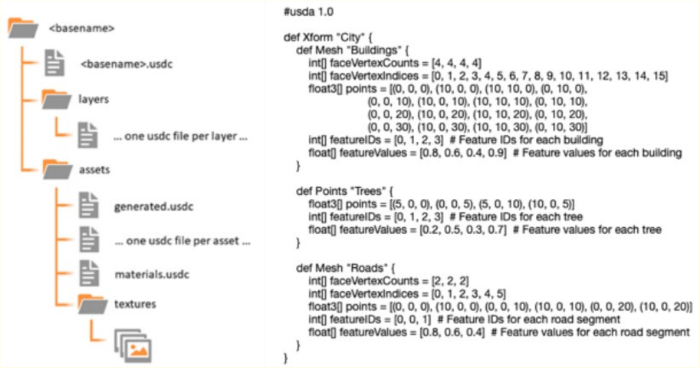


Figure 5: Experimental Instantiation Area "Jardins du MONT", Belfort (France).

Experimental Settings

In the context of modeling urban visual features for the MSUDT and 3D geosimulation, the OpenUSD standard schema emerges as a robust and adaptable framework for representing 3D scenes and assets. Its layered composition and referencing capabilities offer an effective means of organizing and managing intricate urban scenes. Providing a flexible and scalable framework, the schema adeptly captures the geometry, attributes, relationships, and behaviors of objects within a scene. Leveraging a combination of JSON and binary formats, it ensures efficient storage and transmission of 3D data. By incorporating geometry, attributes, and metadata, the schema facilitates precise and detailed descriptions of visual features in files. In essence, USD files encapsulate data that defines the appearance of a scene, subsequently interpreted by rendering applications to generate images on the screen.

To evaluate the effectiveness of the proposed approach utilizing USD standard specifications, a series of experiments were undertaken to develop the digital twin of a housing estate [1]. These experiments utilized a representative dataset of the urban environment, depicted in Figure 6. To address the diverse visual characteristics of various urban residences, such as houses, apartments, and other dwellings, a comprehensive database was meticulously curated. Integral to our algorithmic developments, this database comprises 800 photos capturing a hundred distinct houses. During the data collection process, strict adherence to overlap constraints was maintained to ensure the robustness of our algorithms. The database consists of 799 calibrated image pairs, meticulously organized based on stereovision image matching constraints. The experiments cover four distinct categories, elaborated in Table 3.



```
#usda 1.0

def Xform "City" {
   def Mesh "Buildings" {
      int[] faceVertexCounts = [4, 4, 4, 4]
      int[] faceVertexIndices = [0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]
      float3[] points = [(0, 0, 0), (10, 0, 0), (10, 10, 0), (0, 10, 0),
                         (0, 0, 10), (10, 0, 10), (10, 10, 10), (0, 10, 10),
                         (0, 0, 20), (10, 0, 20), (10, 10, 20), (0, 10, 20),
                         (0, 0, 30), (10, 0, 30), (10, 10, 30), (0, 10, 30)]
      int[] featureIDs = [0, 1, 2, 3]  # Feature IDs for each building
      float[] featureValues = [0.8, 0.6, 0.4, 0.9]  # Feature values for each building
   }

   def Points "Trees" {
      float3[] points = [(5, 0, 0), (0, 0, 5), (5, 0, 10), (10, 0, 5)]
      int[] featureIDs = [0, 1, 2, 3]  # Feature IDs for each tree
      float[] featureValues = [0.2, 0.5, 0.3, 0.7]  # Feature values for each tree
   }

   def Mesh "Roads" {
      int[] faceVertexCounts = [2, 2, 2]
      int[] faceVertexIndices = [0, 1, 2, 3, 4, 5]
      float3[] points = [(0, 0, 0), (10, 0, 0), (0, 0, 10), (10, 0, 10), (0, 0, 20), (10, 0, 20)]
      int[] featureIDs = [0, 0, 1]  # Feature IDs for each road segment
      float[] featureValues = [0.8, 0.6, 0.4]  # Feature values for each road segment
   }
}
```

Figure 6: Dataset sample for MSUDT Implementation with the OpenUSD Standard Schema.

Experiments	***Description***
1- 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.
2- 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.
3- 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.
4- 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.

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

Results Analysis

Our investigation sought to appraise the effectiveness, precision, and efficiency of the urban visual feature modeling process, employing a comparative analysis against prevailing methods in urban simulation and analysis. In the initial experiment, the hierarchical organization facilitated by OpenUSD showcased its prowess in enabling modular development and management of the urban environment. It demonstrated the capability to establish layer dependencies, emphasizing the adaptability and user-friendliness of layered composition and referencing. This capability allowed for the seamless creation of intricate and realistic urban scenes.

The second experiment honed in 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. The support for geometric representations, including polygons, NURBS curves, and surfaces, allowed for precise shape and structure representation. Material and texture assignments further augmented the visual realism of the models. Essenially, this experiment affirmed that the proposed approach using USD standard specifications yielded high-fidelity urban visual feature models.

Moving forward, the third experiment delved into the integration of urban visual feature models into a 3D geosimulation framework and subsequent assessment of simulation results. The integrated model successfully simulated diverse scenarios, encompassing urban planning, traffic simulation, and environmental analysis. Evaluation of the model's performance in terms of computational efficiency and accuracy demonstrated 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 geosimulation applications.

In the fourth experiment, our approach underwent validation and comparison 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 OpenUSD 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.

Metric	***X3D***	***IFC***	***CityGML/CityJSON***	***OpenUSD***
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
Here is the meaning of each metric value.				
Low: Processing times are notably slow, hindering real-time operations. Workflow efficiency is hindered, requiring extensive time for tasks. **Moderate**: Processing times are acceptable but may slow down for complex scenes. Usability requires some familiarity with the system. Manual adjustments are occasionally necessary. Workflow efficiency is reasonable but may be time-consuming. **Comparable**: Processing times are on par with industry standards. Model accuracy is like industry-standard expectations. **Higher**: Processing times are notably fast, supporting real-time interactions. Substantial manual adjustments are often needed. **User-friendly**: The system is intuitive and easy to use for various skill levels. **Reduced**: Manual adjustments are infrequent due to system efficiency. **Improved**: Workflow efficiency is noticeably enhanced, reducing task time				

Table 4: OpenUSD's metrics compared to current standards for urban visual features modeling.

Conclusion and Future Work

This paper has immersed itself in the intricate domain of MSUDT desing and implementation challenges and proffered effective solutions grounded in the OpenUSD ecosystem. Systematically exploring historical developments, conceptual frame-works, and contemporary UDT processing technologies, we identified and confronted critical challenges such as data integration, scalability, interoperability, and security. The advocacy for OpenUSD as a solution has been validated by its open-source nature, standardized approach, and commendable capabilities in handling large-scale 3D models with high fidelity. The experimental application of OpenUSD in a real urban environment yielded promising results, providing tangible evidence of its transformative potential in overcoming the identified challenges. Looking forward, the future of MSUDT research and application holds exciting prospects and avenues for exploration. One paramount aspect involves further refining and expanding the OpenUSD ecosystem to accommodate evolving urban landscapes and technological advancements. Collaborative efforts within the research community can contribute to enhancing OpenUSD's capabilities and addressing emerging challenges. Additionally, the integration of artificial intelligence and machine learning techniques holds promise in optimizing MSUDT workflows, automating data processing, and enriching the predictive capabilities of DT. The practical implications of MSUDT in urban planning and development warrant continued investigation. Further case studies and real-world applications can deepen our understanding of OpenUSD'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 MSUDT and OpenUSD. In the realm of policy and governance, the adoption of standards for MSUDT implementation is crucial. Establishing guidelines for data privacy, security, and ethical considerations ensures the responsible and transparent deployment of digital twin technologies in urban environments. Furthermore, engaging with city stakeholders, including residents and businesses, in the cocreation of DT fosters a sense of ownership and collective responsibility for the sustainable development of urban areas. Our paper not only addresses the immediate challenges of MSUDT implementation but also lays the foundation for a future where OpenUSD 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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