Towards Formalizing Scenario Modeling in Semantic 3D City Models

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Abstract

Semantic 3D city models are a central component of Urban Digital Twins (UDTs), enabling KPI-driven, evidence-based urban planning and decision making. While significant progress has been made in reconstructing models of the existing built environment and various modeling support tools exist, the creation of hypothetical planning scenarios remains time-consuming and the modeling process, as such, insufficiently formalized. In practice, planning scenarios are manually modeled to evaluate potential future states, requiring numerous interdependent geometric and semantic modifications to the base model. Despite the substantial manual effort involved, modeling processes are rarely analyzed systematically. This work addresses this gap by formalizing scenario modeling in semantic 3D city models as a recursive aggregation of atomic edit operations and their dependencies, represented through directed dependency graphs. To distinguish between the effort required to model virtual planning scenarios and the effort required for their real-world implementation, we introduce the concepts of the *'Level of Modeling Effort (LoME)'* and *'Level of Realization Effort (LoRE)'*. Using the City of Munich's scenario modeling activities as a case study, we analyze the substantial manual effort required and highlight the need to formalize the modeling process. The proposed framework provides a foundation for comparing modeling approaches, quantifying efficiency gains, and supporting the development of automated or AI-assisted scenario-generation methods for semantic 3D city models.

1. Introduction

Semantic 3D city models are a core component of Urban Digital Twins (UDTs) and support a wide range of simulations and analyses that inform evidence-based urban planning decisions. Downstream applications such as traffic simulations, solar potential analyses, microclimate simulations, and flood risk assessment rely on geometrically and semantically consistent semantic 3D city models to derive Key Performance Indicators (KPIs) (Biljecki et al., 2015). Advances in computational performance and the development of AI-based surrogate models increasingly enable the rapid evaluation of KPIs (Aderyani et al., 2025, Kastner and Dogan, 2023).

While methods for reconstructing semantic 3D models of existing geospatial objects, such as buildings, from heterogeneous measured data exist and are being further developed (Peters et al., 2022, Wysocki et al., 2023, Kim et al., 2025), semantic 3D city models representing hypothetical planning scenarios, such as the one illustrated in Figure 1, are primarily modeled manually today. In practice, planning teams iteratively modify virtual 3D city models to represent potential design options, which are then evaluated leveraging the same simulation methods used to assess the present state of a city. We use the term "planning" to denote the design of concrete physical measures, e.g., widening a bike lane, adding solar panels, that are subsequently represented in a semantic 3D city model, not statutory or regulatory (land-use) planning.

Urban planning projects are commonly cases of *brownfield scenario development*. This means they are usually not carried out on empty or undeveloped land, but rather in areas with existing uses and infrastructure. In contrast to *greenfield scenario development*, where new planning scenarios are modeled in isolation, brownfield development requires integrating new scenarios into the surrounding environment, connecting seamlessly with existing structures. A redesigned street, for example must seamlessly connect to existing surrounding traffic networks. These connections must be geometrically and semantically sound. For example, there must not be any discontinuities or gaps, and predecessor and successor relationships must match. In practice, however, virtual representations are frequently modeled entirely new as isolated structures. These processes are time-consuming and require heterogeneous geometric and semantic modifications to a semantic 3D city model. Due to requirements on consistency, numerous modifications are interdependent. We hypothesize that stakeholders may favor planning options that appear more promising from the beginning to minimize the risk of committing substantial time and financial resources to model scenarios that are never realized.

The substantial manual modeling effort motivates research into procedural and AI-based approaches for automating scenario modeling. However, despite the manual effort involved, serving as a key motivation, the modeling process itself is rarely analyzed systematically. Existing approaches often fail to capture the structural complexity of scenario modeling, thereby limiting the ability to compare manual, rule-based, and AI-based modeling approaches, quantify potential efficiency gains, and systematically allocate resources across different software systems and standards.

To address this gap, we formalize the process of modeling hypothetical planning scenarios in semantic 3D city models as a recursive aggregation of atomic edit operations and their dependencies. By representing these dependencies as a directed graph, our approach provides a tool-agnostic formalization that captures both the scale and structural complexity of scenario modeling. Furthermore, we conceptualize the Level of Modeling Effort (LoME) and the Level of Realization Effort

Figure 1. Exemplary planning scenario of the Boschetsrieder Street in Munich. Left: Digital twin representing reality. Right: *digital triplet*, cloned from the digital twin and manually modified, representing a hypothetical planning scenario. The modeling process took roughly 20 workdays and involved insertion, modification, and deletion of heterogeneous, semantically rich features, including driving and bicycle lanes, lane markings, pedestrian walkways, vegetation objects, city furniture objects, and more.
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(LoRE) to distinguish the effort required to generate a virtual representation of a hypothetical planning scenario in a semantic 3D city model from the effort involved in implementing such a scenario into reality.

The primary contributions of this work are:

- An analysis of the substantial effort involved in modeling hypothetical planning scenarios, illustrated through real-world case studies.
- The conceptualization of the *Level of Modeling Effort (LoME)* and *Level of Realization Effort (LoRE)* to distinguish the effort required to generate virtual 3D models and their realization.
- A formalization of the scenario modeling process as a recursive aggregation of atomic edit operations.
- A dependency-graph representation to capture the structural complexity of scenario modeling processes.

2. Related Work

2.1 Urban Digital Twins

Originating in Industry 4.0, the concept of Digital Twins has been transferred to the geospatial domain. Extensive research has been dedicated to exploring concepts and implementations, integrating detailed semantic 3D city models, simulation tools, and analytical frameworks to support data-driven and evidence-based urban management (Kolbe et al., 2021, Lei et al., 2023, Deng et al., 2021). Notably, there have recently been efforts to establish agreements on defining standardized approaches towards Urban Digital Twins (UDTs) (German Institute for Standardization, 2024).

Modeling and managing planning scenarios. Today, hypothetical *"what-if"* planning scenarios in semantic 3D city models are primarily modeled manually. Research into the automated generation of such planning scenarios has examined a range of approaches based on procedural modeling (Müller et al., 2006, Kelly, 2021) and generative AI (Du et al., 2026). However, these approaches often struggle to incorporate surrounding structures or to provide the semantic richness required by downstream applications. Additionally, procedural modeling engines require manually formulated generation rules.

Aiming at standardized management of planning scenarios and associated simulation results, the *Scenario Application Domain Extension (Scenario ADE)* has been developed to augment the standardized CityGML data model. The Scenario ADE allows, among others, to represent scenarios that refer to specific city models, as well as input and output parameters that are relevant to simulations and analyses (Schüler et al., 2018, Widl et al., 2018).

Simulations and analyses based on urban digital twins. Semantic 3D city models are widely applied in heterogeneous domains, including, for example, traffic simulation on microscopic and macroscopic scales (Tamminga et al., 2014), urban flood simulations (Andriessen et al., 2024), and more (Biljecki et al., 2015). While physics-based simulation algorithms can take considerable time to produce results, the emergence of AI-based (surrogate) simulations and analyses offers the potential to significantly increase speed, enabling users to explore simulation results in near-real time. In this context, recent research has focused on developing urban data platforms for the decentralized integration of heterogeneous modeling functionalities and simulation models to facilitate collaborative urban planning (Herzog et al., 2025).

2.2 Changes in Semantic 3D City Models

Urban planning actions as complex transactions. A wide range of modifications can be applied to semantic 3D city models. In their work on complex urban planning actions, Sindram and Kolbe propose an ontology for the formal modeling of planning actions by conceptualizing complex transactions on the entities of semantic 3D city models (Sindram and Kolbe, 2014). Exploring the implications of brownfield scenario development, Sindram and Kolbe consider pre-conditions for the applicability of specific actions in their approach. Furthermore, the resources required for the realization of a hypothetical planning scenario are considered in their framework.

Hierarchical modeling of changes. In his research on identifying and interpreting changes in semantic 3D city models, Nguyen proposes a comprehensive data model to represent the various types of transformations commonly observed between successive versions of semantic 3D city models (Nguyen, 2024). The data model distinguishes, among others, between syntactic, geometric, and semantic changes. Edit operations represent a central concept in graph-based change detection and impact analysis for structured data (Chawathe and Garcia-Molina, 1997). Building on this concept, Nguyen distinguishes between property-based edit operations (InsertedProperty, DeletedProperty, UpdatedProperty) and node-based edit operations (InsertedNode, DeletedNode) (Nguyen, 2024). While the approach of Nguyen centers on changes already implemented in the built environment and the virtual 3D model, the focus of this work shifts to prospective changes that have not yet been realized, neither in the semantic 3D city model nor in reality.

2.3 Assessment of Modeling Effort

Cost estimation of construction projects is a long-standing topic of research (Kim et al., 2004, Elmousalami, 2020). In the domain of building information modeling, project cost management is commonly conceptualized as 5D BIM (Smith, 2014). In such approaches, cost information is dynamically linked to 3D models and construction schedules. 5D BIM enables automatic quantity extraction and real-time cost updates as the design evolves, primarily focusing on the financial effort of realizing a planning scenario rather than the cost of generating the virtual representations themselves. Existing research into this direction has investigated the quantification of modeling effort by assessing primarily by time and object count. Modeled components and the duration spent modeling on them are recorded. While this dual quantification allows distinguishing between total and per-object modeling effort, it does not account for interdependencies between different modeling steps (Leite et al., 2011), thereby falling short of capturing a fundamental characteristic of scenario modeling in semantic 3D city models.

2.4 Impact Analysis in Software Engineering

Impact analysis has been extensively studied in software engineering to assess the consequences of changes in complex systems, conceptualized as the set of artifacts directly or indirectly affected by a modification. This impact can be formalized using dependency graphs or traceability relations (Bohner, 1996, Arnold, 1996, Lehnert, 2011, Li et al., 2013), commonly computed as the closure of dependency relations reachable from the initially changed entity (Ryder and Tip, 2001).

3. Scenario Modeling in Urban Digital Twins

We use the term *"semantic 3D city model"* for the geometric-semantic dataset itself, and *"Urban Digital Twin"* for the broader system in which it is embedded, together with sensors, simulation pipelines, and other components. The process of modeling hypothetical planning scenarios in semantic 3D city models is presently often understood in an informal, tool- and organization-specific manner. This lack of formalization limits the ability to systematically analyze modeling processes and quantify effort. Therefore, in this section, we conceptualize the role of modeling hypothetical planning scenarios within semantic 3D city models. We introduce a conceptual perspective that serves as the foundation for the subsequent formalization of the modeling process.

3.1 Scenario Modeling and the Digital Triplet

Our conceptualization of this role aligns with and extends the work of (Sindram and Kolbe, 2014). Beginning with (the duplicate of) a urban digital twin (UDT) representing reality, heterogeneous scenario modeling processes can be applied to produce multiple possible future-state UDT (e.g., UDT$(a, t+1), (b, t+1), \dots (n, t+1)$). Thereby, the concept of a *"digital twin"* evolves into *"digital triplets"*, comprising the real-world entity, its Digital Twin, and additional models representing possible future states.

Each digital triplet is subject to the same simulations and analyses to evaluate KPIs as the UDTs representing the as-is state.

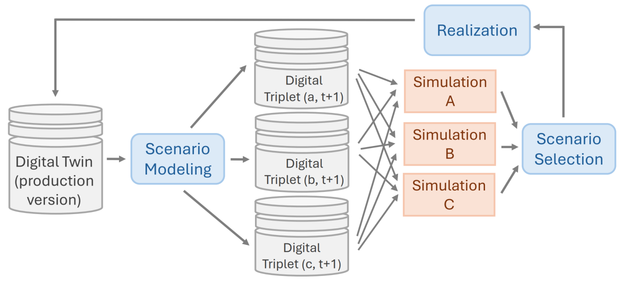

Figure 2. Schematic diagram illustrating the role of scenario modeling in the context of the urban digital twins (UDTs).

Simulation results can then be directly compared with baseline simulations conducted on the current-state UDT, thereby enabling the identification of the most suitable planning scenario. Finally, the chosen planning scenario will be implemented in the real world. Figure 2 illustrates this process in a schematic diagram. Subsequent sections of this work primarily address the semantic 3D city model, which constitutes a fundamental building block of urban digital twins.

3.2 Pre-Conditions and States of Consistency

Assessment of available 3D space. Before modeling an intended modification to a semantic 3D city model is possible, an evaluation is necessary to determine whether the designated site provides sufficient 3D space to accommodate the intended development. Currently, such assessments are primarily performed implicitly and manually, relying on the extensive professional expertise and judgment of urban planning practitioners.

Consistency criteria. At the beginning and end of every scenario modeling process, semantic 3D city models must be in a consistent state. Consistency criteria are diverse and presently not uniformly formalized. Buildings, for example, must be located on the ground and not overlap with other city objects. Furthermore, additional case-specific constraints, such as heritage protection, can be imposed on scenario modeling processes. Maintaining a consistent state is a fundamental prerequisite for any semantic 3D city model to support downstream applications such as simulations, (spatial) analyses, and visualizations. Relevant consistency criteria can depend on the concrete application of the modeled scenario. Scenarios for traffic simulations, for instance, have other requirements than scenarios for urban climate simulations.

4. Scenario Modeling in the City of Munich

In the City of Munich, 3D modeling of hypothetical planning scenarios represents a key component of urban planning processes. Virtual 3D representations serve as the foundation for a wide range of applications that support KPI-driven decision-making. These include, for example, microscopic and macroscopic traffic simulations, microclimate analyses, lighting simulations, and 3D visualizations designed to facilitate citizen participation and collaborative urban planning.

The responsibilities for developing and applying these virtual representations are distributed across multiple departments with domain-specific expertise. To meet the requirements of the heterogeneous application domains, the departments develop

Project Name	Project Context	No. of Variants	Modeling Duration [workdays per person]	Spatial Extent [ha]
Bahnstrecke Daglfing-Johanneskirchen	Urban Development Plan	2	90	287.88
Vision Boulevard Sonnenstraße and Herzog-Willhelm-Park	Open Space District Plan for the Downtown Area	1	60	92.90
Boschetsrieder Straße 2.0	Bicycle Referendum Munich	1	20	109.74
Hackenplatz with Hackenstraße	Funded Project REACT-EU	1	16	14.45
Riedlerstraße	Bicycle Referendum Munich	1	12	47.80
Freiham Fahrradstraße	Bicycle Referendum Munich	1	10	107.84
Ungererstraße	Bicycle Referendum Munich	1	10	38.79
Zeppelinstraße	Bicycle Referendum Munich	1	8	33.47

Table 1. Overview of 8 selected planning projects in the City of Munich for which virtual representations of hypothetical scenarios were created. Modeling durations, number of variants, and spatial extents highlight the substantial manual effort.

tailored models optimized for their respective use cases. For example, models intended for visualization may incorporate high-resolution textures or deliberately emphasized features (e.g., exaggerated curbstones), whereas models for macroscopic traffic simulation are reduced to abstract topological representations. This federated modeling approach necessitates effective coordination and communication between the different departments.

Over the past five years, significant resources have been invested in manually creating such 3D models. Within the context of the *Digital Twin Munich*, 3D scenario models were created for 19 diverse urban planning projects. Table 1 provides an overview of selected project sites along with their respective approximate modeling durations and spatial extents. The table demonstrates that creating a single virtual 3D model, such as the one illustrated in Figure 1, can take up to several weeks. For most of the planning scenarios listed in Table 1, a single design variant was modeled from plans provided by architectural and civil engineering offices in CAD or PDF format. These plans themselves were not part of the subsequent iterative federated modeling processes, which typically involved iterative modifications that were implemented manually and using procedural modeling tools such as ESRI CityEngine (Kelly, 2021). Currently, scenario modeling practices in Munich lie at the intersection of greenfield and brownfield approaches. While the planning scenarios are generally embedded into the context of the city, many new scenarios, particularly those created for visualization purposes, are developed entirely new. In particular, semantic connections to structures surrounding the planning scenario are frequently not thoroughly realized in the models.

As Table 1 illustrates, in practice, the required modeling effort varies significantly depending on the type and complexity of modifications. Regular structures, such as LoD2 building models or bicycle lanes, can often be modeled efficiently, partly also due to advances in procedural modeling techniques. In contrast, more detailed and complex structures, such as LoD3 building models with intricate facade elements (e.g., balconies, moldings, intricate windows), as well as civil engineering structures like bridges, tunnels, or railway underpasses, require substantially more manual modeling effort. In general, a higher level of detail is associated with a higher modeling effort. Additionally, considerable effort is required to adapt the digital terrain model, particularly in areas involving railway infrastructure, such as tram tracks. It must be ensured that the modified terrain is topologically consistent (e.g., without holes), integrates seamlessly with surrounding unchanged areas, and aligns correctly with other urban objects, preventing inconsistencies such as floating city objects. Furthermore, substantial modeling effort is dedicated to ensuring that newly created geometric structures comply with corresponding standards, such as ISO 19107 (International Organization for Standardization (ISO), 2019). For instance, polygons must be properly closed and free of duplicate vertices, and overlapping geometries must be resolved.

The activities in the City of Munich show that the effort required to model virtual 3D representations of hypothetical planning scenarios is considerable and must therefore be considered during project budgeting and scheduling processes. This highlights the potential of further research into scenario modeling and management methods. Variations in modeling effort across diverse types of planning scenarios motivate a formalization of the modeling process, enabling improved comparability and, in the future, an improved quantification of modeling effort.

5. Conceptualizing Level of Modeling Effort

Effort in the context of urban planning can be assessed from varying perspectives. On the one hand, there is effort required to implement intended planning scenarios in the real world. It can be assessed from different perspectives, including financial expenditure, duration, or administrative effort involved. On the other hand, as Section 4 illustrates, substantial effort is required to model virtual 3D representations of planning scenarios. Therefore, we propose to formally distinguish these two kinds of effort:

- Level of Modeling Effort (LoME)
- Level of Realization Effort (LoRE)

We consider LoME and LoRE as sets that can be operationalized in varying ways. LoME can, for example, be operationalized by assessing the number of operations in the modeling process or by evaluating modeling duration. Operationalizing LoRE is beyond the scope of this paper. Existing construction cost estimation methods, such as 5D BIM (cf. Section 2.3), can provide a starting point. The effort of modeling and the effort of realization are independent of each other and are typically significantly distinct. A planning scenario that is easy to model on a computer in semantic 3D city model might be implemented in reality only under significant effort or vice versa. The Overall Level of Effort (OLoE) is then composed of LoME and LoRE:

$$OLoE := LoME \cup LoRE \quad (1)$$

To enable more efficient resource allocation for these modeling tasks, a deeper understanding of the underlying processes and their associated effort is required. Formalizing the modeling workflow represents a fundamental step toward advancing research in this area.

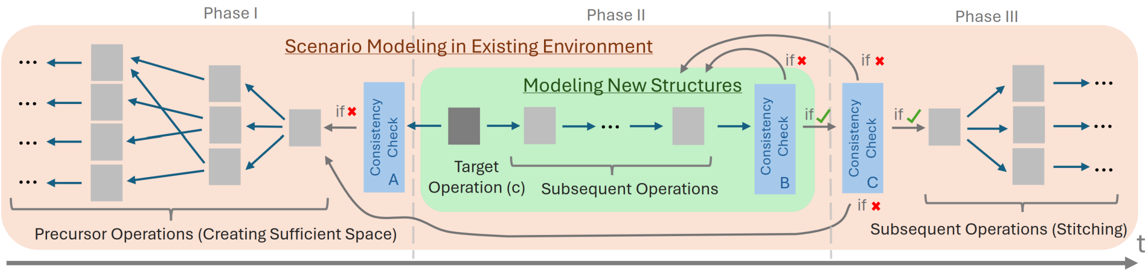

Figure 3. Schematic diagram illustrating the process of scenario modeling in existing environments. Precursor operations, necessary to create sufficient 3D space to accommodate an intended planning scenario, are not considered in *greenfield scenario development* approaches. Dependencies between different operations are illustrated as blue arrows.

6. Formalizing the Modeling Process

Modeling effort is not determined solely by the type of the modeling process. In brownfield scenario development, the previous state of the semantic city model and the structures surrounding the new planning scenario contribute to the modeling effort. *'Widening a bike lane'*, for example, might be a simple modeling task in a park area with no directly adjacent buildings and plenty of green spaces. In such a scenario, widening the bike lane might simply require removing several existing vegetation objects. The same kind of tasks, *'widening a bike lane'*, would be more complex and involve a higher modeling effort in an inner city, which includes driving lanes, tram tracks, pedestrian walkways, buildings, and other city objects such as traffic lights, post boxes, lanterns, and more. Modeling such a scenario can involve complex dependencies between required operations. This motivates the need for a formal representation of the modeling process, which serves as the foundation for quantifying effort.

6.1 Modeling as a Recursive Process

Operations and edits. We begin the formalization of the modeling process by conceptualizing the *operation* as the fundamental building block of every scenario modeling process. An *operation* c_f modifies a feature f that is part of a semantic 3D city model M. Formally, an operation is defined as a function that maps a semantic 3D city model to another semantic 3D city model, with the set of all semantic 3D city models $\mathcal{M}$:

$$c_f : \mathcal{M} \to \mathcal{M} \tag{2}$$

Let $\mathcal{C}$ denote the set of all possible operations. The sequential application of operations can be expressed by functional composition. For two operations $c_i, c_j \in \mathcal{C}$ and a city model $M \in \mathcal{M}$, we obtain

$$(c_j \circ c_i)(M) = c_j(c_i(M)). \tag{3}$$

Aligning our definition with the conceptualization of *edit-operations* used in structured data and graph-based change detection systems (Chawathe and Garcia-Molina, 1997, Nguyen, 2024), we apply the recursive aggregation design pattern illustrated in the UML diagram in Figure 4, considering an edit-operation as a basic operation affecting a feature in M. Edit operations can be aggregated into more complex *CityModelChanges*, introduced by (Nguyen, 2024), affecting higher-level semantic structures in the model. For example, when a building is translated, the changes in the coordinates of its individual points, which are basic edit operations, can be interpreted as a single translation operation affecting the top-level

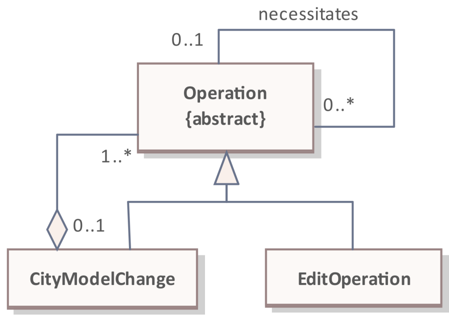

Figure 4. UML diagram illustrating the concept of an operation. Following a recursive aggregation design pattern, we consider edit operations as atomic operations. *CityModelChanges* consist of one to many operations that can be either *CityModelChanges* themselves or basic edit operations. Any operation might necessitate precursor operations and/or subsequent operations.

feature. Formally, a *CityModelChange*, denoted as Δ, can be interpreted as a composition of operations, where the product operator denotes functional composition.

$$\Delta = \prod_{i=1}^{n} c_i \tag{4}$$

Modeling process as a set of operations. Illustrated in Equation 5, scenario modeling processes can be interpreted as finite sets of independent operations c applied to different features $f, g, ...n \in M$. For example, a traffic sign might be moved a few meters, and an unrelated building might be augmented by an additional storey.

$$S = \{c_f, c_g, \dots, c_n\} \subset \mathcal{C}. \tag{5}$$

Applying the set of operations to an existing semantic 3D city model M_0 representing existing reality yields a hypothetical planning scenario M_{new}, which is, again, a semantic city model:

$$M_0 \xrightarrow{c_f} M_1 \xrightarrow{c_g} \dots \xrightarrow{c_n} M_{new} \tag{6}$$

If the operations in S do not introduce conflicts, their order of application does not affect the resulting model state.

Formalizing scenario modeling in existing environments. As illustrated in Figure 3, before the *target* operation (e.g., the widening of a bike lane) can be conducted, it must be ensured that the designated site provides sufficient 3D space to accommodate the proposed development. This makes the initial *target operation* dependent on a variety of *precursor operations* that

have to be conducted in advance. For large-scale projects, target operations can potentially require massive sets of precursor operations. In the project *"Boschetsrieder Straße 2.0"* in Munich, among other measures, biking lanes were widened by approx. $90cm$, pedestrian walkways were widened to approx. $2-5m$, 170 new bicycle parking spaces were created, and 40 additional trees were placed. Only after all necessary precursor operations are conducted, and no remaining dependent presursor operations remain, the target operations themselves can be applied. Finally, subsequent operations necessary to seamlessly stitch the newly modeled structures into their surroundings must be applied.
This modeling process involves at least 3 consistency checks. The first check (A) evaluates whether sufficient space has been created to accommodate the intended planning scenario. The second check (B) is required to assess the internal consistency of the newly modeled structures. In the event of this check failing, modelers must return to the modeling process of the new structure itself. If consistency check B evaluates positively, a third consistency check (C) has to be applied to verify the consistency of the newly modeled structures with their existing surroundings. In the event of this check failing, modelers need to go back either to the precursor operations or to the part of the process where the new structures were modeled for adjustments.
As Figure 3 illustrates, the systematic consideration of *precursor operation* and the connection of the new design with the existing surroundings in phases I and III, represent the primary differences between *brownfield scenario development* and *greenfield scenario development*. The latter only encompasses the modeling steps within the green box in Phase II. Frequently, procedural (Kelly, 2021), and deep-learning-based methods (Du et al., 2026) aiming at automated planning scenario generation primarily focus on *greenfield scenario development* by creating new objects and not taking existing structures and precursor operations as well as stitching operations into account.

Dependency function and closures. To formalize the dependency between a target operation and its directly dependent precursor and subsequent operations, we define a function $Dep(c)$. This function maps an operation to a set of required dependent precursor and subsequent operations on the same feature or on other features to maintain consistency of the overall city model. Evaluating $Dep(c)$ yields both *"direct"* precursor and subsequent operations, denoted with an apostrophe, with respect to the operation c.

$$Dep : \mathcal{C} \rightarrow 2^{\mathcal{C}} \tag{7}$$

$$Dep(c) = \{c'_1, c'_2, \ldots, c'_n\} \tag{8}$$

Equation 8 allows us to define the subsequent closure of c, written as $\mathrm{Closure}(c)$. We define it recursively as:

$$\mathrm{Closure}(c) := \mathrm{Set}\left(\{c\} \;\cup \bigcup_{c' \in \mathrm{Dep}(c)} \mathrm{Closure}(c')\right) \tag{9}$$

The closure represents the full set of dependent operations that are required when applying a target operation c. We extend the closure concept to sets of operations:

$$Closure(S) := \bigcup_{c \in S} Closure(c) \tag{10}$$

The fully resolved planning scenario then becomes:

$$S_p := Closure(S) \tag{11}$$

Dependency graph. As exemplarily illustrated in Figure 3, the closure of an initial operation c can be understood as a dependency graph G_c:

$$G_c := \{V_c, E_c\} \tag{12}$$

with the nodes:

$$V_c := Closure(c) \tag{13}$$

and the directed edges:

$$E_c := \{(x, y) | y \in Dep(x)\} \tag{14}$$

Leveraging this conceptualization, the function $Dep(c)$ can be interpreted as the set of all nodes directly reachable from c in one step. The formalization proposed in this work captures the structural complexity originating from interdependencies between operations.

6.2 Identifying Affected Features

The dependency function $Dep(c)$ formally captures all operations directly required to maintain consistency when applying a target operation. Therefore, identifying affected features constitutes the practical evaluation of $Dep(c)$. The following paragraphs outline concrete geometric and semantic mechanisms through which $Dep(c)$ can be operationalized.

Identifying spatially affected features. Geometric changes alter the spatial and topological configuration of objects and can propagate through physical adjacency, leading to cascading updates in neighboring structures. To obtain the set of all geometric changes necessary to ensure the consistent state of a planning scenario, all features that are spatially affected by an operation have to be identified. For this purpose, the Dimension-Extended 9-Intersection Model (DE-9IM) (Clementini et al., 1993) can be leveraged. A feature can, for example, be considered spatially affected if a change in the DE-9IM between features in a defined neighborhood can be observed after conducting an operation.

Identifying semantically affected features. In contrast to spatial changes, semantic changes modify the meaning, classification, or logical relationships of elements without necessarily affecting their geometric or topological properties. Semantic changes can propagate through physical adjacency and logical and semantic relationships, extending beyond the immediate spatial neighbourhood of a feature. Identifying features affected by semantic changes in another feature can occur through multiple mechanisms. One possibility involves explicit referencing, wherein a feature is directly linked to another via a unique identifier. This method is typical in models that encode predecessor-successor relationships, such as those used in semantic representations of street spaces (Beil, 2025). In such cases, determining the full set of affected features necessitates traversing all features that reference or are referenced by the modified feature. An example could be the reversal of the direction of a one-way street. Affected features can also be identified through assessing implicit relationships, which rely on contextual or external information rather than direct references. Changing the designated use of a building from *"residential"*

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to *"school"* or *"kindergarten"*, for example, may require adjacent roads to adopt lower speed limits to ensure the safety of children. Any operation can induce cascades of both geometric and semantic subsequent operations. A geometric modification of the roof of a building model, for example, can necessitate the semantic change of *"roofType"* attribute.

7. Discussion

7.1 Priorization of Promising Planning Scenarios

The current practice of modeling hypothetical planning scenarios in the City of Munich highlights that, in addition to the effort required for real-world implementation, the substantial effort involved in virtual modeling must also be taken into account to achieve a more realistic estimate of the total project effort. As a result, the effort associated with modeling processes represents not merely a technical consideration but may also influence planning processes themselves. In particular, we hypothesize that the high cost and time requirements of 3D modeling can discourage the exploration of a wide range of alternative planning options. Instead, stakeholders may prioritize planning variants that appear more promising in advance, to reduce the risk of investing significant time and financial resources in modeling scenarios that are ultimately not realized. This phenomenon is emphasized by the increasingly fast availability of simulation results, which can potentially render scenario modeled effortfully in weeks practically obsolete in seconds or minutes.

7.2 Scenario Modeling Beyond 3D City Models

This work focuses on the modeling of hypothetical planning scenarios in semantic 3D city models. Urban digital twins additionally comprise components such as distributed sensor systems, stakeholder relationships, and regulatory frameworks (Moshrefzadeh, 2025), which, while critical in practice, are not explicitly considered here.

7.3 Formalizing the Modeling Level of Effort (LoME)

The manual effort required for different modifications to semantic 3D city models depends on the software and tooling used, as well as on the geometric and semantic granularity of the underlying data model. The same what-if scenario can yield different LoME values depending on whether a coarse or a highly detailed data model is applied. Progress in modeling support systems or the automation of repetitive design steps might contribute to reducing the overall manual effort involved in modeling hypothetical planning scenarios. To facilitate the comparability of heterogeneous modeling processes and enable the quantification of efficiency gains by automation methods, a tool-independent operationalization of the LoME concept, introduced in Section 5, would be beneficial. A proxy for LoME could be the cardinality of the closure of a set of operations. The two bike-lane scenarios introduced in Section 6 illustrate this: the park scenario, requiring only the removal of a few vegetation objects, yields a small closure and thus a low LoME, whereas the inner-city scenario, involving driving lanes, tram tracks, pedestrian walkways, buildings, and city furniture, yields a substantially larger closure and correspondingly higher LoME.
Because LoME is defined over operations on a data model, the concept can be applied to heterogeneous geospatial standards, including two-dimensional representations. This dependency also means LoME could inform the choice of data model (e.g., CityGML vs. IFC) for a given application, by making the modeling-effort trade-offs of different standards explicit. To better reflect practical modeling effort, future work is required to parameterize weights for different types of operations.

7.4 Implications for Automation

The formalization introduced in Section 6 can serve as the theoretical backbone of structured, semantically enabled scenario generation methodologies. Formalized dependency relationships can be applied to systematically decompose complex modeling tasks into a meaningful sequence of operations required to achieve a desired modeling outcome. LoME is inherent to the scenario modeling process and independent of applied modeling support tools. Procedural modeling, generative AI, and functionalities embedded in authoring software can therefore be interpreted as different ways of grouping together the atomic operations that sum up to LoME.
Our objective is not to replace urban planners with automated scenario-generation methods. Rather, we aim to provide planners with generative tools that enable the exploration of a wider range of planning alternatives by automating the generation of 3D scenario models. This increases the chances of identifying better planning solutions.

8. Conclusion

In this work, we highlight the important role of scenario modeling in urban digital twins, particularly for enabling evidence-based urban planning. Leveraging the City of Munich as an example, we demonstrate that current approaches to modeling virtual representations of planning scenarios often require substantial manual effort, while also providing a strong foundation for future research on automated scenario generation.

To distinguish between the effort required to model virtual planning scenarios and the effort required for their real-world implementation, we introduce the concepts of the *'Level of Modeling Effort (LoME)'* and *'Level of Realization Effort (LoRE)'*. Furthermore, we introduce a formalization of the processes of modeling planning scenarios in semantic 3D city models. We conceptualize scenario modeling as a recursive process composed of atomic edit operations and their dependent operations necessary to maintain consistency. Leveraging our formalization of the modeling process, we illustrate the differences between brownfield and greenfield scenario development.
Future research will look at empirically validating the proposed framework, operationalizing the dependency function discussed in Section 6, calibrating an effort metric, and investigating centralized, SDDI-compliant, storage of scenarios or digital triplets in versioned databases (Moshrefzadeh, 2025).

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