KNOWLEDGE DRIVEN RULE-BASED BUILDING GEOMETRIC DIGITAL TWIN CONSTRUCTION – STATE OF ART REVIEW

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Abstract

Automatic construction of the building geometric digital twins (gDTs) is implemented based on the scanned data from the existing buildings. The highly detailed gDTs necessitates the top-down construction method informed by the predefined building knowledge. This paper reviews the building rules used for the model-driven building indoor environment gDTs construction. It is found that these knowledge is fragmented and lacks systematic analysis. The research categorise these rules into three groups and proposes an Ontology-based knowledge graphs (KGs) approach for organising this knowledge. This method aims to integrate rules for gDT construction to establish a knowledge system for the further research.

Introduction

The emergence of gDTs sheds light on both academic and practical perspectives in the digitalisation journey of the AECO industry (Dou et al., 2023). DTs are the virtual replicas of physical assets, processes, or systems that enable stakeholders to visualise, monitor, and analyse their projects with unprecedented precision. gDTs focus on the static information in the model, and these are meanly the geometric information (Pan et al., 2023). An accurate and semantically-rich gDT ensure a foundation decision-making system for the building condition real-time monitoring, simulation and optimisation.

The process of gDTs construction of existing buildings typically involves the steps of: 1) scanned data collection, 2) scanned data processing, and 3) gDTs recreation. There are numerous methods for surveying and data acquisition (Volk et al., 2014). Subsequently, the collected data should be detected, segmented, and classified efficiently. The first two steps involve most of the technically complex tasks to form the essential prerequisites for gDTs construction. Numerous studies focus on the data collection and processing workflow, while fewer research work assesses the gDT recreation process. The gDTs creation work is regarded to be the 'last mile' process and a simple procedure to convert the information extracted from collected data into a structured format. However, the efficient gDT recreation requires the prior knowledge of the buildings, which including the object shapes, the identifications of objects and their relationships. The rule-based construction method can help avoid the obvious irrationality in the gDT construction process (P. Tang et al., 2010). However, there is no research focuses on reviewing and analysing the building rules that frequently used in gDTs construction to the authors' knowledge.

Building grammar is utilised to present the common building design logic and the structural topology of the building objects (Hu et al., 2019). During the gDTs construction process, building grammars are mentioned in the literatures emphasising the rules that are related architectural design principle. These can be summarised as multiple rules being employed as pre-established knowledge to minimise the dependence on the accuracy of the scanned data. This knowledge serves as the crucial supports to gDTs construction and inference.

KG plays a crucial role in the knowledge management field. Ontology-based KG is a method of representing knowledge, which utilises ontological structures to categorise and interconnect the various entities and their relationships (Bassier et al., 2020). There are some existing ontology-based KGs that can present the building topology and its semantic information (Rasmussen et al., 2020). However, there is still a gap in how to present the knowledge transferring from the scanned data to create the gDTs and to integrate the gDTs with the specific building domain knowledge.

The research objective of this paper is to review the rules used in gDTs construction phase. In addition, the conceptual framework of an ontology-based KG is then introduced to not only present the model-driven gDTs construction rules but also allow the further domain knowledge integration. The proposed KG shall benefit the researchers with direct and intuitive access to the building knowledge as a top-down gDTs creation guidance. Based on the objective, the research questions are listed: a) what knowledge is frequently used as a guide of gDTs creation process, and b) how to organise them in an ontology-based KG as the knowledge base. The proposed KG will be further enriched in the following research with the detailed description of the entities, properties and the reasoning and querying rules, which will facilitate the construction of the semantically-rich gDTs and the inference of hidden objects that are occluded during the data collection process.

Methodology

State of art review is an important knowledge capture method to design a domain KG (Wang et al., 2022). This paper conducts a systematic review and concludes the knowledge utilised for the rule-based indoor environment gDT construction (see Figure 1). Leveraging the keywords that precisely encapsulate the target papers, the searches for 'digital twin generation' and 'scan to BIM' is implemented within the databases like Web of Science and Google Scholar, covering the past decade (2014 – early 2024). After excluding studies outside the relevant fields, a total of 825 papers were initially identified. Through further selection stages, which involved assessing content completeness and scrutinizing abstracts, only 18 papers that introduce the rules for model-driven gDTs construction of building indoor environment were chosen for further detailed analysis.

This knowledge is categorised into three perspectives, which are shape rules, topological rules and semantic rules. Different categories of rules work on the various aspects of information. The shape rules typically work on the geometric attribute of the one category of building element, including the building components and space. The topological rules contribute to the establishment of the spatial relationships between the building elements. While the semantic rules refer to the guidelines or constraints based on the underlying model's semantics. The semantic information can support to the realisation of various potential functions of gDTs, such as the hidden elements inference. Some of the rules are analysed and visualised through a case of the Civil Engineering Building in the University of Cambridge.

Based on that, we developed the conceptual framework of an ontology-driven KG. These rules shall be transformed into the key components of the gDTs construction KG, which are class, properties, constraints, and reasoning rules. The KG acts as a reusable knowledge base, offering a structured representation of the current state of knowledge during the gDT construction process.

Knowledge-driven rules of gDT construction

Knowledge-driven gDTs construction approach emphasises the top-down concep from the required output information. The quality of the scanned data is not a primary factor influencing the output, but the rules adopted during the creation process. Architectural grammar can be considered as the fundamental principle of the building design. In 1994, the knowledge-based computational method for architecture design was explored. It represents a complex procedure grounded in primitive elements and design rules (Carrara et al., 1994). Currently, the knowledge-driven rules based on the building grammars can be used for the building asset remodelling (Nikoohemat et al., 2021), prediction of the building componence configurations (Chen & Liu, 2023), building compliance checking and interior space navigation (Nikoohemat et al., 2021). The Table 1 concludes the key research about the knowledge-driven rule-based methods, and the corresponding target elements.

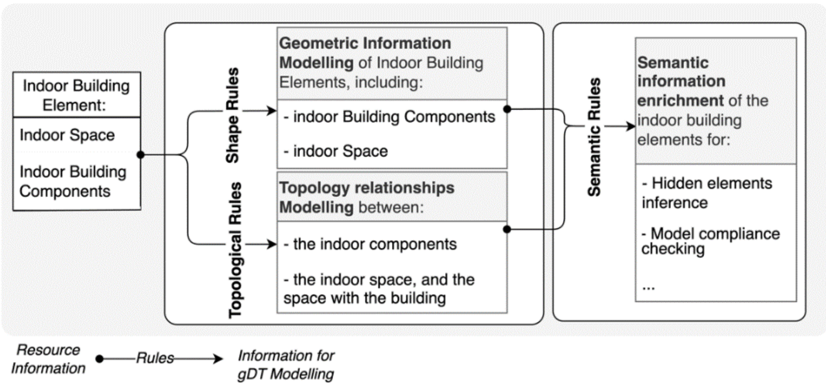

Table 1 Rules of building indoor environment gDTs construction

Research	Elements	Model-driven reconstruction method
(Khoshelham & Díaz-Vilariño, 2014)	interior walls	**shape-driven** rules for indoor wall layout reconstruction
(Becker et al., 2015)	interior hallway, rooms, staircase	three **topology-driven** rules for indoor layout and staircase reconstruction
(Ning et al., 2015)	Walls, windows, doors and roofs	**shape-driven and topology-driven rules** for the object-oriented in the scenes
(Abdollahi et al., 2023; Thomson & Boehm, 2015)	Interior walls	**shape-driven rules** for the geometric restrictions of interior walls
(Hu et al., 2019)	indoor room type inference	sixteen indoor room **topology-driven** rules to infer the room type from room layout
(Yang et al., 2019)	interior walls, roof, ceilings, doors, windows, stairs	**semantic-driven** representation for indoor environment reconstruction, especially the semantic representation of stair space

(Bassier & Vergauwen, 2020; Tran et al., 2019; Tran & Khoshelham, 2020)	interior walls	**topology-driven** rules for interior walls construction
(Nikoohemat et al., 2021)	indoor environment	eight **topology-driven** rules for building indoor component
(Cai & Fan, 2021)	interior rooms, doors	six **topology-driven** rules of the doors' position in the wall to infer spatial relationship of rooms
(Tang et al., 2022)	interior walls, roof, ceilings, doors, windows	**shape-driven** rules of planes and **semantic-driven** rules for 3D object-based indoor environment modelling
(Park et al., 2022)	indoor environment including main structural elements and furniture	**shape and topology-driven** rules of the boundary boxes of the indoor environment objects including floor, wall, column, door, window, table, chair, sofa and bookcase
(Chen & Liu, 2023)	indoor room layout inference	six **semantic-driven** rules to infer interior room layout from exterior building boundaries
(Kellner et al., 2023)	interior walls, windows and rooms	**shape-driven and topology-driven rules for the geometric features of the walls, windows and rooms;**
(Yang et al., 2023)	interior walls and indoor rooms	**topology-driven** rules of two walls, three walls and four walls
(Drobnyi et al., 2024)	interior components and space	**topology-driven rules** ('same-space', and 'same-object') for the indoor components and space

Shape rule-driven construction

The common building objects, such as the walls, floors, roofs, doors, windows, and space should be object-oriented constructed in the gDT creation process. The shape rules can be applied in both building elements modelling and interior spaces modelling.

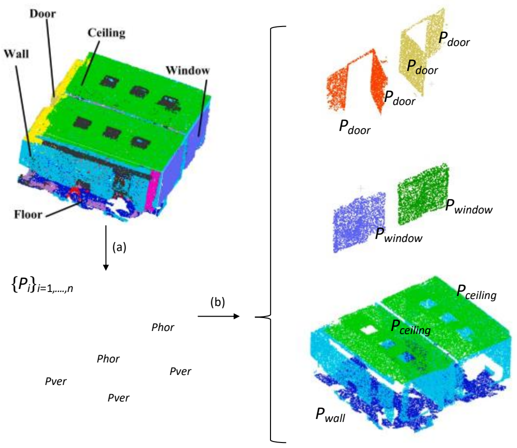

Figure 2 Shape rule-driven for building components construction (Tang et al., 2022) *(a) Decompose the data into planar primitives (b) semantic information enrichment to the planar primitives for further refinement.*

Shape rules for the building components

Wall modelling is an important task in the indoor gDT construction, typically requiring fitting with parallel and smooth surfaces rather than tessellated-as modelling. Bassier & Vergauwen (2020) defined a set of positional relationships as the foundational rules for the multiple cuboid walls. These relationships can serve as the prior knowledge for wall object creation, including: 1) intersection, 2) orthogonality, 3) blending, and 4) direct connection. Thomas and Boehm (Thomson & Boehm, 2015) proposed three geometric restrictions while the wall is generated, which are reject small wall, extend large wall and merge close planes with similar normal. Tang et al. (2022) utilised a grammar-enhanced method to decompose the entire scene into planar primitives using a two-level shape rule, based on the segmented point cloud clusters (refer to Figure 2). The first level of rules divides all planar primitives $\{P_i\}_{i=1,\ldots,n}$ into three categories according to their orientation: vertical planes (P_{ver}), horizontal planes (P_{hor}), and other planes (P_{oth}). The second level of rules further select the planar primitives that exhibit structural characteristics of the interior model and assign the semantic information to them. The characteristics are confirmed based on the geometric constrains and spatial orientation to identify doors (P_{door}), windows (P_{window}), ceilings ($P_{ceiling}$) and walls (P_{wall}).

The shape-based rules for identifying building components aim to discern the features of specific object categories. This approach is efficient as a reason of considering the ground truth shape of building elements. However, there is a lack of consistency in defining primitives and their geometric relationships across various building elements. Different researchers have adopted distinct methods for defining shape features. For instance, the positional relationships of interior walls are defined differently in the study by Bassier and Vergauwen (2020) and Khoshelham and DíazVilariño (2014). Despite these differences, both studies essentially describe the same real-world relationship between interior walls. In such scenarios, ontology-based KG holds the significant potential to facilitate the fusion of these diverse definition methods via unifying terminology.

Shape rules for the building internal space

Shape rules can be effectively applied to generate parametric indoor spaces (Abdollahi et al., 2023; Khoshelham & Díaz-Vilariño, 2014; Tran et al., 2019). This approach involves positioning cuboids within a zone defined by enclosing points to identify the space. Subsequently, topology relationship rules are typically employed in the next stage of space modelling.

The 4-tuple, $G = \{I,N,T,R\}$ is used to define a space in shape rules (Tran et al., 2019). Among that, I, represents the initial shape, providing the foundational form from the beginning of modelling. It serves as the baseline and starting point for further transformations. N denotes non-terminal shapes, which are intermediary forms during the modelling process. And T signifies terminal shapes, marking the end shape of space division. R refers to the production rules that indicate the transformation process. The relationships of these parameters can be presented as: $R : A \rightarrow B : cond., A \in N, B \in V, V = N \cup T$. The rules ($R$) can be categorised to different types, such as the initial shape place rule (R_{place}), the merging rule (R_{merge}) for two non-terminal shapes and the split rule (R_{split}) for space decomposition (Khoshelham & Díaz-Vilariño, 2014; Tran & Khoshelham, 2020). For instance, the R_{place} is presented through a transformation H, applied to the initial cuboid S, *where* $R_{placecuboid} : S \rightarrow HS$.

Shape rules can also define the relationship between building component and space as $G = \{N,T,R,S\}$, which represent the non-terminal space, terminal space, grammar axiom and starting symbol, respectively (Nikoohemat et al., 2021). With the basic elements defined, the relationship between two or more components can be further explored using topology rules. These two 4-tuples represent typical shape rules used for space construction, established on the similar conceptual basis but expressed in varying ways. Knowledge fusion is essential to merge similar concepts across different 4-tuples, aiming to realize a consistent workflow in the shape rule-driven space construction method.

Topology rule-driven construction

The logic applying topology rules for indoor 3D construction lies in establishing constraints on the interrelated topological connections of space and building structural elements. This method effectively addresses the challenges posed by incomplete and occluded elements in scanned point cloud data (PCD) (Ning et al., 2015; Tran et al., 2019; Yang et al., 2019).

Topology rules for indoor components

The building indoor environment comprises spaces and the building components, including structural elements, furniture and building service equipment. The allocation of walls is important for constructing the building indoor environment. The topological relationships between two walls (*collinear, perpendicular and intersect*), three walls (*T shape and pseudo T-shape*) and four walls (*cross shape*) are discussed (Yang et al., 2023). These relationships are important to overcome the occluded points at the corner in the collected PCD. Besides, the room boundary surface parameters can be adjusted based on the associated wall objects and the room object will be accurately rebuilt accordingly. Nikoohemat et al. (2021) highlighted the 8 potential relationships between 3D objects in building indoor elements, which are *disjoint, meet, equal, overlap, contain, cover, inside* and *coveredBy*. Furthermore, within the '*meet*' relationship, three sub- relationships are defined: support, supported and attachment.

The topological relationships between windows and walls are discussed by Kellner et al. (2023). These relationships can be utilised to not only generate the wall elements with attached door and windows, but also represented in the constructed gDT model. In addition, the integration of shape and topological relationships among the indoor building elements optimise the PCD semantic segmentation results to help with the high accuracy gDT construction. Park et al. (2022) define relationships of the indoor building element based on the boundary boxes of the objects, the spatial vectors of the boxes, and their referenced objects and referenced vectors. Except for the definition about the relationships between the objects, the topological relationships between planer surfaces are also explored (Drobnyi et al., 2024). The relationships of '*same-space*' and '*same-object*' are defined as a basis to form the topological relations between objects and spaces.

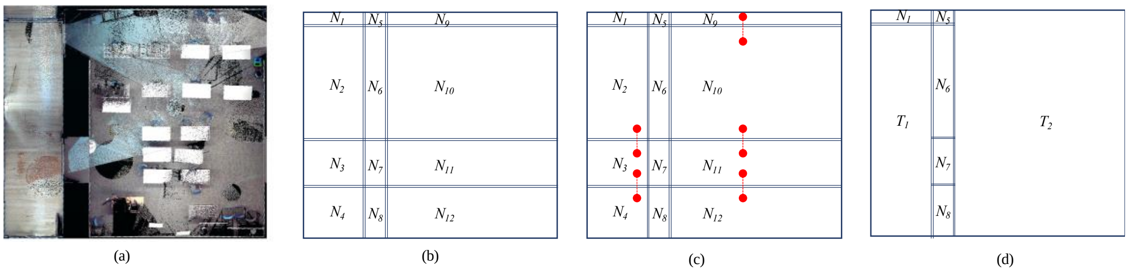

Figure 3 Merging non-terminal connected spaces (Civil Engineering Building in UOC as a case presenting the merge rules from (Tran et al., 2019): (a) top view of the selected scanned data, (b) top view of the cuboid shapes classified as the interior spaces, and defined as N (Non-terminal space), (c) find the adjacent spaces that without the common wall, and (d) the result with the merged cuboid defined as T (Terminal space).

Different research defines the various aspects of topological relations between the building indoor environment elements, which are laser scanning points, planer, object with the same or different semantic classification. The objectives of most of the rules are creating the semantic label to the disordered point cloud to construct the gDTs with not only the geometric, but also the topologic information. All the building elements with the same architecture style share the similar sets of features. However, the rules are fragmented. The systematic fusion of the rules can boost the knowledge-driven gDTs construction workflow.

Topology rules for indoor space

The indoor environment of a building not only consists of the building components but also the space. A room is defined as the terminal space enclosed by the walls, and it can be defined by the topological relationships of the spaces that compose them, and the building components, such as door or walls. These relationships are crucial for knowledge-driven gDT construction and inference. Tran et al. (2019) proposed a procedure for the room configuration rebuild including six rules: *placement, classification, adjacency, connectivity, merge and containment* rules. Three of the rules show the topological relationships of spaces including terminal and non-terminal spaces, which are: *adjacency, connectivity, and containment*. These relationships can be presented as: $R[t]: \{A1,A2\} \rightarrow \{A1[t],A2[t]\}: cond$, where, $R[t]$ is one of the constraints rules; $A1$ and $A2$ are terminal shapes or non-terminal shapes; and *cond* is the condition that identifies the topology relationship between shapes. The application of merge rule to combine two non-terminal spaces is exemplified in Figure 3, using UOC civil engineering building as an example.

The topological rules for the indoor space not only aid in room construction but can also facilitate the identification of further semantic enrichment (Cai & Fan, 2021; Tran et al., 2019). For instance, if two rooms are connected through an adjacency relationship, they share one common wall or a segment of it. Conversely, if a room partially shares a common wall with several rooms, it might indicate that this room is a corridor or hall space. Additionally, more semantic information can be inferred from the identification of room functions, such as the navigability of the space, and the existence of a door element. However, these relationships and the causation among these rules are not systematically organised. Integrating these into a KG could streamline the space construction and further support the reasoning of semantic information as proposed earlier.

In multi-story scenarios, the stair space is analysed by Yang et al. (2019). It is characterised as the composite space that connects two storeys. The stair space, denoted as S_{stair}, comprises two components: the stair-occupied space S_{sto} and the stair connection space S_{stconn}. The definitions of S_{sto} (green space) and the S_{stconn} (blue space) are illustrated in the Figure 4. Furthermore, the stair space connects with the slab free space S_{sf}, and the stair connection space, intersects with the associated slabs S_{slab}. This relationship can be expressed as: $S_{stair} = \{S_{sto}, S_{stconn}\}$, $S_{sf} = S_{slab} \cap S_{stconn}$.

Becker et al. (2015) emphasised the significance of hallway as critical elements within the building indoor environment. They proposed a strategy for constructing L-system hallway using spatial split rules and characteristics unique to hallway areas in buildings. Three functional control approaches are identified based on the topology relationships of segmented space, which are the *ActivationControl, LayoutSetting* and the *ConsistencyConstraints*.

The rooms, hallways or corridors and staircases are the typical indoor space. Tran et al. (2019) and Cai & Fan (2021) focused their research on individual rooms and corridors. Yang et al. (2019) examined the relationships of staircase spaces. However, current research lacks an integrated approach that encompasses the entire building interior space. The management of knowledge from these state- of-the-art studies could significantly enhance the capacity for indoor space construction in gDTs and provide robust evidence for subsequent semantic information retrieval.

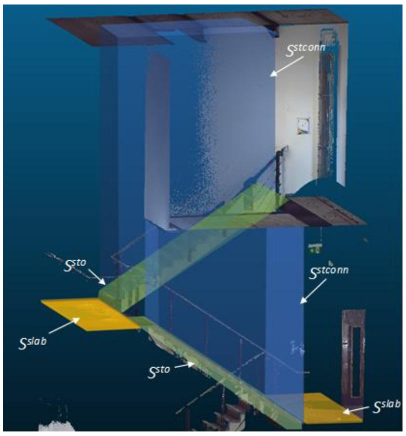

Figure 4 Definition of a stair connection space (Yang et al. 2019) *shown in the UOC case.*

Semantic rule-driven construction

The parametric and semantic properties of indoor spaces and components are pivotal information sources in current gDT construction practices (Jarząbek-Rychard & Maas, 2023; Liu et al., 2023). Semantic rules are commonly applied following the detection of building elements through shape rules, and the assessment of the topological relationships. For a comprehensive gDT, it is crucial to consider the unified and consistent characteristics of the entire indoor model, rather than focusing on isolated parts such as walls, doors or staircases (Yang et al., 2019). The importance of semantic rules is to generate the attributes for building elements beyond the parametric information that facilitate further utilisation. For example, the semantic rules are defined as classification and declassification to determine whether a room is an interior space or external space by Tran and Khoshelham (2020). This categorisation aids in supporting functions like indoor path planning. This research elaborates how semantic rules power the hidden element inference in the gDT construction process. Furthermore, this section reviews the key literature on the semantic rules applications and summarises the main semantic rules.

Hidden element inference

The knowledge-driven construction methods help with the prediction of space types (Hu et al., 2019; Xie et al., 2021). It provides a robust framework for building model construction, fostering a detailed and nuanced understanding of hidden objects and spaces within a 3D model. Chen and Liu (2023) underscored the importance of space syntax theory and design conventions, especially in the context of Singaporean dwelling units. This approach facilitates the inference of room types within a building.

Currently, most of the methods for inferencing building indoor environments focus on space or room predication. However, with semantic rules, further predication can be conducted. Hidden element inference, for instance, can be realised if default semantic information is available as prior knowledge. For example, the paths of the building pipeline could be predicted as guided by semantic rules by knowing the locations of the MEP (mechanical, electrical and plumping) terminals, and the spatial relationships between the equipment rooms and these terminals. However, there is less research contributing to this workflow.

Knowledge graph for gDT construction

A KG is a network of interconnected entities such as objects, events, concepts, represented in a graph format. In this graph, nodes typically symbolise entities or concepts, while edges represent the relationships between them (Bassier & Vergauwen, 2020). KGs utilize ontologies to define their structure, with Resource Description Framework (RDF) serving as a standard for describing the relationships (edges) within the graph.

The KGs can be utilised in building the knowledge of object identification and 3D model construction, and contributing to the knowledge fusion to the specific domains after the gDTs are constructed. Park and Cho (2022) develope the Entity-relationship diagram (ERD) to bridge the connections among point cloud, point, object, material, location. This semantic information is stored and converted in the point dimension to guide the information modelling of the building. The rules used to generate the gDTs can also be modelled in the KG, they can be regarded as the prior knowledge to facilitate the gDTs construction process. Hmida et al. (2013) propose the knowledge-based PCD detection and annotation strategy with an OWL ontology language, the Semantic Web Rule Language (SWRL) and the 3D processing built-ins. They divide the scene into various domain concepts depends on their characteristics and geometric relationships. This solution was tested in the railway objects. The knowledge from Geographic Information System (GIS) system is also integrated in the OWL structure for the further information enrichment to the 3D model. In addition, the approach of 'scan-to-graph' (STG) is proposed by Werbrouck et al. (2020). The STG method aims to integrate the Scan-to-BIM results with the sources of real-world asset via the semantic web technologies to overcome the uncertainties (occlusions, internal structure, etc.) of the collected data.

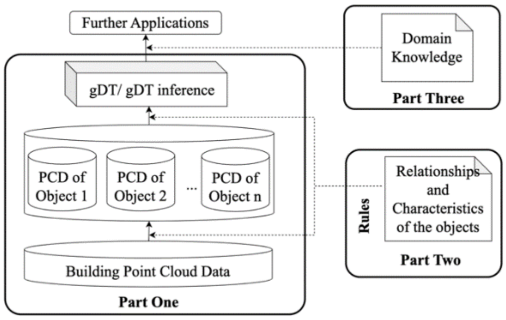

Figure 5 Conceptual framework of gDT construction KG

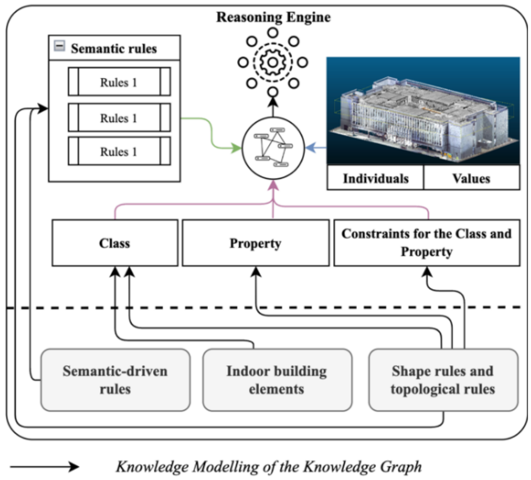

Figure 6 Key components of gDTs construction KG

Currently, there are less literatures focus on the KG development on both: 1) gDTs construction process and 2) the knowledge fusion for the further gDT applications, especially for the indoor building objects. Moreover, there are only limited rules are stored in the current KGs. In this paper, we developed the initial conceptual diagram of the knowledge graph to meet the two requirements with the considerations of shape, topological, and semantic rules. The structure of the ontology-based gDT knowledge graph is shown in Figure 5.

The first part of the framework focuses on transforming building PCD to object PCDs, and then the PCDs are converted to be the gDTs. The shape, topological, and semantic rules can be derived from the characteristics from the objects, and the relationships between the objects. Additionally, this step involves inferring parts of the building that might be occluded or hidden in the scan data based on the prior knowledge. The second part aims to establish the knowledge base (including the object characteristics and relationships) for the rules generations to facilitate the process of part one. This mainly involves the rules that discussed in the review parts of this paper. The establishment of the knowledge base of the rules can also be integrated with the existing ontologies that are commonly used, such as the Building Topology Ontology (BOT) (Rasmussen et al., 2020). In the third part, domain knowledge is utilised to enrich the gDTs for further development. This includes integrating the gDTs with other databases, such as energy consumption or environmental data, and refining the model for specific applications like simulation or analysis. The continuous improvement and updating of the gDTs are crucial to ensure they remain an accurate and useful representation of the physical structure.

Figure 6 presents the key components of the KG and the knowledge modelling mapping relationships from the building knowledge to the ontology-based KG. To enrich the ontology-based KG, building elements shall be converted to the classes, and the shape-driven and topology-driven rules will be presented as the classes, properties, constrains or the reasoning rules for the classes and properties of the KG. The semantic rules shall be expressed with the rules for the gDTs processing, semantic information enrichment and occluded gDTs inference. The objective of the proposed KG framework is to offer a comprehensive approach to enhance the gDTs construction workflow by incorporating the shape, topological, and semantic rules, ultimately paving the way for more sophisticated and accurate model-driven gDTs construction of building indoor environment.

Discussion

Understanding the indoor architectural rule and modelling it in a structured framework can support the recreation the building elements and the prediction of unreachable places in buildings. However, there are still some challenges in the current rule-based gDTs construction approaches. For example. the construction of the nonplanar surfaces and the non-Manhattan buildings are one of the big challenges (Tang et al., 2022; Tran et al., 2019). Moreover, the important connection building elements like doors and stairs are often manually added. Besides, some rules may only be applicable for specific types of buildings, such as churches or small-scale residential houses. The knowledge driven rule-based gDTs construction methods are important and should be further developed to compensate for the imperfections in the data collected from the physical world.

Conclusions

This paper has reviewed and analysed the rules in knowledge driven rule-based gDTs construction workflows from the perspectives of shape, topological, and semantic rules. It also proposes an initial conceptual KG framework for the structured representation of these rules and their interrelationships. Further development on the KG will encompass a broader range of building objects. Additionally, the continuous development of information reasoning and querying rules will also be conducted to facilitate the inference of hidden building objects and the enrichment of semantic gDTs.

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