Smart Spatial Ontology: Bridging Semantic Ontology to Spatial Topology

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ABSTRACT

This paper proposes a feasible approach named òSmart Spatial Ontologyó for converting ontological declarations into topological relations and geometric features, which would then assist users to retrieve relevant cases from the case library. The purpose of this project is to extend the knowledge representing abilities of our design case library, which develops smart retrieval of spatial topology within plan drawings for assisting architectural design.

Keywords: case-based design, case library, spatial topology, semantic ontology.
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1 INTRODUCTION

Case libraries are usually implemented using relational database technology, which requires selecting the most specific common features of the cases. The selected explicit features serve as the index mechanism of the case library. However, an index mechanism that uses explicit features often overlooks the acquisition, re-indexing, and generalization of the implicit knowledge of cases, such as the representation of spatial topologies and semantic associations among physical components and vacant spaces.

Eastman proposed the building product model (BPM), which consisted of three types of information: semantic, topological, and geometric information [4]. Eastmanõs insight also initiated research on the building information model (BIM), which is applied in modern computer aided architectural design (CAAD) tools and is widely adopted in the architecture, engineering, and construction (AEC) fields. However, most implementations of BIM still lack the necessary information model for storing spatial topology, as well as representing and retrieving design information of spatial topology. On the other hand, it is usually difficult to collect the complete BIM files of an important precedent to store into a case library, and it is unnecessary to rebuild the BIM files of a design case for applying case-based design. Hence, the unstructured information of design cases, such as the scanned images of design drawings, are usually easily collected and stored into a case library. The implicit information of the unstructured files, such as semantic, topological, and geometric information of building spaces, usually cannot be indexed and retrieved.

This project is a follow-up study of two previous projects named òSpatial Topology Retrieval (STR)ó [12] and òOpen Case Study (OCS).ó [11] Using previous research results, such as the interactive encoding and retrieving tools of spatial topology, and the classified design patterns detected by data mining algorithms, this project introduces semantic ontology approaches into the case library for establishing the semantic associations among physical components and vacant spaces. Based on the results of applying text-mining and ontology-based techniques in previous studies, it was found that the design patterns require more semantic explanation in order to connect the designerõs prior knowledge. Without appropriate semantic association, or a òpredicationó in the ontology triple, it will be difficult to provide explanations of why two building components or spaces should be adjacent, connecting, or combined.

2 THE APPROACH OF SMART SPATIAL ONTOLOGY

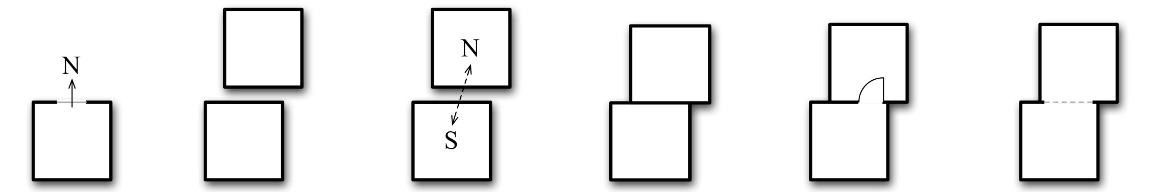
Design knowledge usually is implicit, especially within graphic information such as plan drawings, and cannot be simply represented by explicit features. For example, the dining room of a house should be more suitably connected to the living room because of the following association: “dining room Ÿ service Ÿ living room.ó The òserveró association is similar to a predicate in an atypical triple set of ontology. However, the semantic associations among spaces should be far beyond the òservedó and òservantó spaces of Louis Kahnõs insight, and usually vary with different architects and design situations. Therefore, a processing cycle consisting of the three types of design information emerges from previous studies: (1) the òsemantic ontologyó of building components and spaces is declared; (2) the òtopological relationó among building components and spaces is translated; (3) the ògeometric featuresó of building components and spaces are interpreted; (4) fulfillment of the òsemantic ontologyó is checked.

Although architects seem to utilize this kind of knowledge declaration, transformation, or interpretation every day, a convenient tool for facilitating this processing cycle is still lacking. On the other hand, the converting algorithms among the three types design information are absent in BIM. Therefore, this paper proposes an ontology-based approach named òSmart Spatial Ontology (SSO)ó for converting ontological declarations into topological relations and geometric features, which would then assist users to retrieve relevant cases from the case library. The purpose of this project is to extend the knowledge representing abilities of our design case library, which develops smart retrieval of spatial topology within plan drawings for assisting architectural design.

2.1 Encoding Spatial Topology

Although the modelling, representation, and retrieval of spatial topology are critical issues for research on geographic information systems (GIS), they are often overlooked in present CAAD research. However, many design theories, principles, and rules of architectural design are expressed in terms of topological relationships, such as space coordinates, viewing sights, or circulation relationships [7]. Most BIMs implement geometric parameters of physical components that lack semantic associations with spatial topologies, which are necessary for architectural design thinking and reasoning. This drawback has created difficulties not only in the application of BIM in the early stages of architectural design, but in the indexing and retrieving of implicit knowledge of design cases as well.

In the previous study, spatial topologies have been modelled into three detectable and three operational types for encoding spatial topology [12]. The three detectable spatial topologies are (1) opening, (2) separation, and (3) orientation based on the geometric information of spaces. The three operational spatial topologies are: (1) adjacency, (2) connection, and (3) combination when an adjacent topology has been satisfied (Fig. 1).



(a) Opening (b) Separation (c) Orientation (d) Adjacency (e) Connection (f) Combination

Fig. 1: Six basic types of spatial topologies.

However, spatial topology usually is only the representation of explicit features of how spaces were composed in a plan drawing rather than the implicit design knowledge of why those spaces should be composed in that way in the plan drawing. For example, an architect may convert the òserviceó association between dinning room and living room into connective or combining topology, but the òserviceó association is not the only predicate that a learner of the design case can infer reversely from connective or combining topology. The opening interpretation of spatial topology means that design cases involved have the potential to be reused for different situations, but also blocks the efficient indexation of implicit knowledge behind the spatial topology and the effective association with designerõs concepts. Therefore, a formal declaration of the conversion from semantic association to spatial topology is necessary for indexing, retrieval, and reuse of implicit design knowledge behind spatial topology, and ontology-based mechanism should be one of the most plausible approaches.

2.2 Semantic Ontology of Design Knowledge

Ontology is a knowledge engineering technique and a data model to facilitate knowledge sharing and reusing. A knowledge chunk in an ontology can be represented by a triple set of òsubject,ó òpredicate,ó and òobjectó [6]. The òpredicateó presents the semantic relation among knowledge objects, and determines how an intelligent agent reasons with and validates an ontology by first order logic or other formal logic. Therefore, the declaration of a òpredicateó means linking knowledge objects by causal or semantic relations. Whether for artifical intellegence [6, 7] or philosophy, the meaning of an ontology usually implies that contents and structures of a concept are fixed and static to keep them correct and consistent in a knowledge domain. However, this constraint may satisfy most domains except the design industry.

As education scholars declare, ò*designers reason from cases, not from principles.*ó Designers are educated to transform or interpret cases, not directly imitate precedents [1]. Although most geometric and topological information of building components and spaces should be fixed and static within built precedents, the interpretation of a built precedence still may change with the times and technology. Even old cases can still inspire solutions for new issues such as green building design. For example, an architect may quote the òVilla Savoyeó by Le Corbusier as an energy-saving solution because he recognizes the energy-saving features of the stilt style building and the roof garden within the case. Therefore, design knowledge usually is flexible and varied with design situations, and not easy to formalize into a common and shared ontology.

Based on Gruberõs definition, an ontology should be ò*a formal, explicit specification of a shared conceptualizations* [7].ó But architects usually are educated and encouraged to challenge existing specifications of conceptualizations in their domain, and may not like to share their design concepts before they won competitions. Nevertheless, when users of a case library found some new but implicit features of cases, a formal and explicit ontology still is very useful for indexing, retrieving, representing, and reusing their recognitions. In the previous study, an adaptable and extendable ontology-based annotation system named òOpen Ontologyó [10] was therefore established to formalize the metadata of a house design case library named OCS [11] (Fig. 2). However, the òpredicateó classes of Open Ontology are very simple and only four types of semantic associations, which are of òsame-as,ó òis-a,ó òhold-by/has,ó and òpart-ofó relations based on WordNet [5]. Therefore, this project improves the metadata-authoring tool of OCS, and bridges the semantic ontology to spatial topology for assisting in reusing design cases.

2.3 Bridging Semantic Ontology to Spatial Topology

The òsemantic ontologyó of building components and spaces is a kind of declarative knowledge. However, any representation of declarative knowledge usually involves some kinds of bias of the knowledge holders [2]. Therefore, the òpredicateó classes of spatial topology should be kept open and allow users to expand and modify the thesaurus based on their recognitions. As the STR allows users to annotate spatial topology on a plan drawing, SSO allows users to freely annotate a semantic association between a spatial topology and existing metadata in Open Ontology. However, the four basic semantic associations of Open Ontology still can help implement the self-organizing ability of an ontology based on the hierarchy of semantic associations, such as inheritable atoms from parents and automatically generalizing classifications.

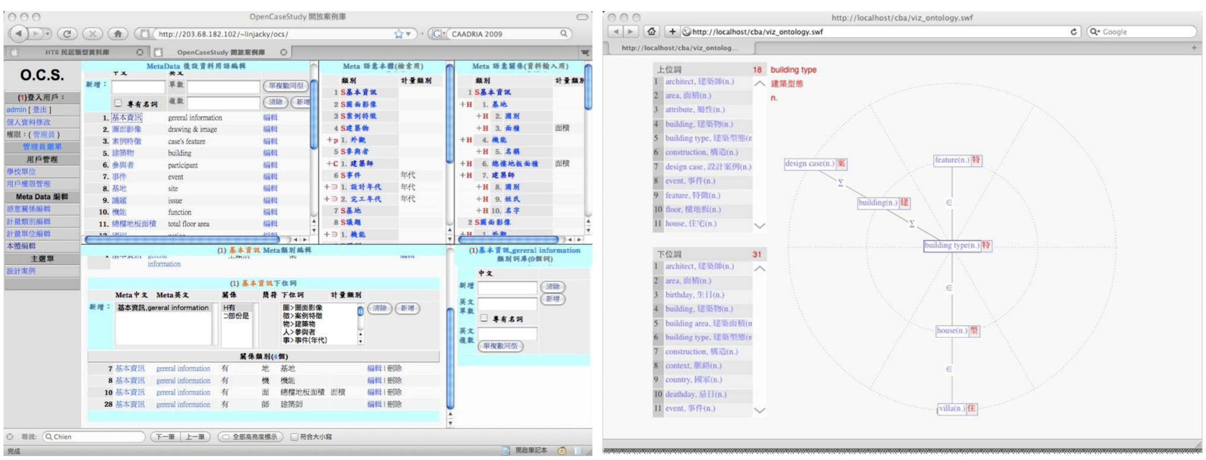


Fig. 2: The interface of the Open Ontology in OCS: (a) the editting interface of Open Ontology, (b) the visual indexing of keywords in the Opne Ontology.

For example, a user can annotate an adjacent topology of two bedrooms with òsame-as Ÿ private zone,ó a connecting topology of a bedroom and a bathroom with òpart-of Ÿ suit,ó a combining topology of a living room and a dining room with òis-a Ÿ public zone,ó or an opening topology with òhas-a Ÿ view.ó Based on the self-organizing abilities of Open Ontology (Fig 2), SSO can automatically index, classify and retrieve relevant spatial topologies and their cases by these four basic semantic associations.

3 IMPLEMENTATION AND PRIMARY EVALUATION OF SMART SPATIAL ONTOLOGY

As the Open Ontology project is not intended to develop a fully functional ontology-authoring or knowledge acquisition tool. SSO based on the Open Ontology on is devoted to bridging semantic ontology to spatial topology for improving the knowledge representation abilities of the case library named OCS. By the semantic associations of spatial topologies, SSO can improve the retrieved results of the graphic-based searching mechanism of STR, then assists users to learn design knowledge more efficiency from the plan drawings of cases.

3.1 Implementation of Smart Spatial Ontology

The database of OCS applies MySQL, and its accessing interface is implemented by PHP and Flash. STR extends the interactive encoding interfaces of spatial topology by the simplified JAVA technology of PROCESSING [13]. With the modern web-based interface technology emerging, SSO integrated the modern Web-based interface of jQuery JavaScript library and interactive manipulations based on PROCESSING to improve the interface of Open Ontology and STR.

3.2 Manipulations of Spatial Ontologies

Formal declarations of an ontology usually concern with tedious indications of textual and numerical attributes of many knowledge chunks. As annoying parametric inputs of a BIM usually confuse architects, ontology-authoring tools such as Protégé usually perplex architects who are educated to think by graphics and drawings. On the other hand, knowledge-acquiring tools usually utilize a top-down approach and focuses on the validation and consistency of a knowledge domain.

However, architects can acquire knowledge chunks from partial and incomplete information such as photos and drawings of design cases, and allow those chucks to conflict within different cases or situations. Therefore, SSO applies a bottom-up approach and implements intuitive and graphic manipulations of spatial ontology, which are extended from the STR's interface. Based on the self-organizing ability of four basic associations in Open Ontology, SSO assists users to annotate their recognitions of spatial topology in a plan drawing of house cases. Fig. 3 demonstrates the STR-based visual interface of SSO, which can directly encode semantic ontology on a topological layout of a house plan drawing in OCS.

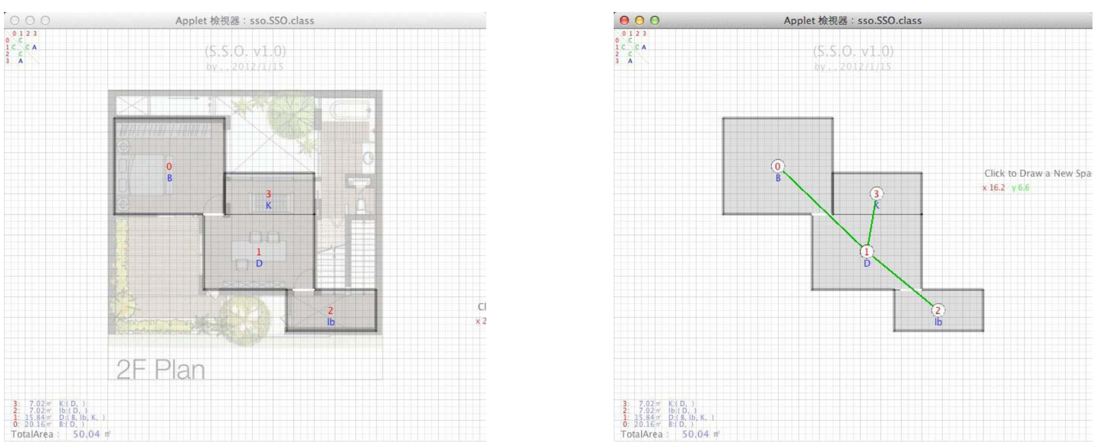


Fig. 3: The prototype of SSO's encoding interface based on STR: (a) the composition of rectangle spaces over a house plan image, (b) the visualization of spatial topologies among spaces.

3.3 Primary Evaluation of Smart Spatial Ontology

To efficiently store, index and retrieve design cases, the classification of design case features is critical for developing a case library. Yet, researchers have argued that: (1) classification of case features is meaningful and useful only with respect to a specific purpose at hand; (2) but how a designer recognizes the features of a case is a function of their personal experiences, (3) therefore useful characteristics of cases usually cannot be known in advance [3]. Therefore, an interpretative tool, which can assist users to represent their personal recognitions, should be more helpful than a prior and static mechanism of classifications for helping users to study existing or new cases.

Freely textural annotations such as tags of popular Web 2.0 sites are simple, efficient, and user-friendly means for indexing and retrieval of unstructured information. However, ill-organized tags cannot avoid confusing problems of design knowledge representation, and usually are not formalized enough to implement a software agent for automatic processes. Therefore, SSO has three advantages than other approaches: (1) the triple set of a knowledge chunk as the prior data structure in assisting users to efficiently organize design knowledge of spatial topology, (2) the basic four semantic associations, and (3) predefined knowledge classes in the Open Ontology as the prior inference mechanism in assisting implementing a software agent which can automatically organize relevant spatial topology.

4 DISCUSSIONS

Design knowledge representation of cases is the major bottleneck of applying CBD and CBR in the field of architectural design. However, most approaches usually overlook formal representation of design knowledge within architectural design cases, and ignore the assistance for representing personal recognitions of users. For architectural precedents before BIM development, useful design information within cases was usually ill-defined or unstructured, let alone formally represented for a machine agent to automatically organize design knowledge. For example, the semantic attributes such as òvillaó or òrow houseó building types cannot explain how and why the spaces in a house case are composed into the houseõs plans. Hence, the design knowledge about cases was usually implicit and cannot be indexed or retrieved. STR in prior studies assist the indexing and retrieval of topological and geometric information of unstructured house plans, and SSO in this study assists the formal ontology representations of reasons of composing spaces in a house into the plans. The conversion of three types of design information provides the following discussion on the study of SSO.

4.1 Open Ontology vs. Closing Topology

The first knowledge bottleneck of spatial topology is the definition of a spatial topology, and STR answers this question. However, the possible spatial topologies of a house plan are limited and can be predefined as shown in Figure 1. However, the possible reasons of a spatial topology tend to be open and vary with the experiences and knowledge of the analyst. Most approaches ignore the necessary opening of interpretations because of technological restrictions, and subsequently block possible usages of personal and partial knowledge sharing. As CBR only applies partial solutions of a case to solve a problem, a partial and incomplete ontology is still useful for learning and retrieving partial design knowledge. SSO is able to assist users in building a small, partial, but formal ontology of a house plan, which in turn assists users in retrieving the situational knowledge inputted by analysts or experts (Fig 4). The divergence of the thesaurus in ontology usually causes inconsistent problems. By prompting known classes in Open Ontology, SSO voids over divergence of the thesaurus in the library and assists users in building a partial and incomplete ontology of a house plan. However, appropriate inconsistency maintains more possible reuse of design cases.

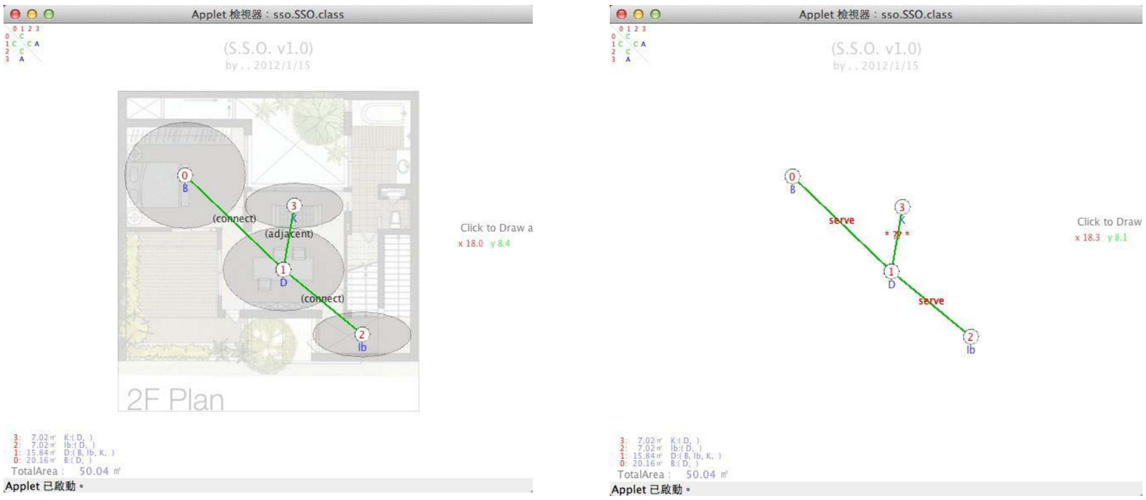


Fig. 4: The visualization of (a) spatial topologies of a house plan, and (b) their ontology in SSO.

4.2 Topological Assignment vs. Geometric Validation

Due to the ill-defined nature of spatial allocation problems, there is a mutually interacting process between the indicators of spatial topology, which define the design objectives or problems; and modifications of spatial geometry search for solutions. Based on previous STR studies, SSO inherits the validation algorithm, which automatically modifies relative positions of spaces based on spatial topology. For example, SSO tries to maintain adjacent spaces when they are assigned adjacent topologies.

However, the validation algorithm is too simple to automatically solve all conflicts when a user encodes spatial topology. On the other hand, the SSO interface provides intuitive indicator, immediate response, and visual reminder for dealing with conflicts, thus assisting users in solving conflicts and validating their assignments of spatial topology. Although the possible spatial topologies are limited, highly varied representations of spatial geometry maintain highly reuse of design cases. However, the efficiency of the validating algorithm has been proven in prior studies, therefore SSO still saves time of revising topological assignments and geometric modification of spaces.

4.3 Spatial Geometry vs. Spatial Ontology

Smart Geometry is the technique that uses computing rules to generate complex architectural components, which are difficult to produce and control by traditional methods. However, present CAAD tools have paid too much attention to coordinating the physical geometry of architectural components, with insufficient considerations in recognizing and converting between semantic ontology and spatial topology of architectural design. Hence, users are able to implement complex building forms in BIM, but cannot check a space within a project regardless of whether the requirements of the building program are satisfied. It is necessary to build a tool to check whether the topology and geometric information of spaces satisfy the declarations of the building program. Hence, SSO of this study devotes to building the bridge between three types of design information.

The ontology in SSO not only assists the geometric validation of spatial topology, but also bridges semantic ontology to topology and geometric information. For validating the ontology, a semantic association bridges a spatial topology with a known class in Open Ontology. Hence, SSO represents the design knowledge of a spatial topology then assists users of the case library in indexing and retrieving relevant cases by semantic associations. For example, a user is able to annotate a **ò**has-a Ÿ view**ó** association selected from existing annotations of **ò**opening**ó** topology on the **ò**living room Ÿ opening Ÿ a lake**ó** topology in the Douglas House by Richard Meier, and help other users to retrieve by the query of **ò**living room Ÿ has-a Ÿ view.**ó** Based on the prototype of SSO, it is possible to make BIM tool smarter by implementing spatial topology and geometry using smart spatial ontology.

5 CONCLUSIONS

The development of an ontology usually focuses on the formal representation of domain knowledge for sharing or reusing by humans or software agents. However, the shared degree of conceptualizations usually decreases with the scope of the domain experts. For example, clients of different cultures or architects of different design studios may not hold the same design concepts about how to assess spatial topology. Therefore, the development of SSO dose not attempt to implement a complete tool of authoring spatial ontology, but extend the knowledge representing ability of OCS by bridging the classes of Open Ontology to the spatial topology of STR with semantic associations. For avoiding confusing and un-formalized problems of free annotations, the basic four semantic associations of Open Ontology can assist the OCS library to automatically organize spatial ontology annotated by users.

However, since there are fewer possible spatial topologies than common semantic associations and relevant knowledge classes, it was found that the translation of semantic ontologies to spatial topologies should be a convergent process. On the contrary, the semantic interpretations and geometric translations of spatial topologies usually become open and divergent [9]. Therefore, spatial topology plays a critical bridge in the information processing of **ò**semantic ontology Ÿ topological relation Ÿ geometric feature**ó** of spatial layouts in early design stages. However, how this type of information processing will appear in different stages of architectural design still need more investigations.

6 ACKNOWLEDGEMENTS

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