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## Abstract

This article discusses interaction between multimodal representations of architectural design knowledge, particularly focusing on relating explicit and implicit types of information. The aim of the presented research is to develop a computational environment that combines several modes of representation, including and integrating different forms of architectural design knowledge. Development of an interactive digital-models library and ontological model of architectural design factors are discussed, which are complementary in nature. In a time when BIM software is seen as embodiment of domain knowledge and the future medium of architectural design, this paper presents an interaction between ontological representation of architectural design knowledge and its embodiment in interactive models, thus focusing on the process of design and design space exploration. In the digital environments that we propose, representation of different formats of knowledge, such as visual, linguistic or numeric, are integrated with relational and procedural information, design rules, and characteristics. Interactive search and query based on contextual constraints, and parametric variation of the model based on the information received from ontology are the underlying drivers for design exploration and development.

## I. Introduction

The nature of architectural design, seen as information-centric process, is such that it leads from incomplete to complete, abstract to concrete, and conceptual to precise descriptions. It is a non-linear process that requires analysis, evaluation, synthesis, and decision-making, thus entailing constant information flow between the designer and environment. The types of information vary depending on the stage in the design process, and tend to transfer from general to specific, where the initial stage involves information about the requirements, building types, environmental and contextual aspects. Later phases require specialized explicit data, such as products, materials, and standards. Discrepancies between explicit and implicit information impose challenges for computational tools and applications.

This paper discusses multimodal representation of architectural design knowledge as a method for linking explicit and implicit types of information. While currently prevailing methods of representing information about architectural design is through Building Information Models (BIM), the aim of this research is to develop a computational environment that integrates several modes of knowledge representation—linguistic, numeric, geometrical, and procedural. This article presents an investigation into interaction between ontological representation of architectural design knowledge and its embodiment in interactive models of know-how, having visual expression. Interactive digital-models library has been developed to serve as referents during design process [1]. Algorithmically modeled design knowledge and know-how contained in referents have been proven to be useful for digital design [2]. Ontological model of architectural design factors has been developed to capture conceptual knowledge associated with building design [3], [4]. Types of factors include environmental, structural, physical and contextual aspects, and are represented through ontology. Ontology contains rules, characteristics and relationships associated with design factors.

The complementary nature of these two types of representation promises advantages in terms of integrative system that contains both. The benefits are representations of different formats of knowledge, relational and procedural information, design rules, and characteristics. Interactive search and query based on contextual constraints, and parametric variation of the model based on the information received from ontology are the underlying drivers.

The article first discusses distinct types of design knowledge representations, differences between explicit and implicit knowledge, Building Information Models and the need for representations of design knowledge which would allow exploration of conceptual space and precedent knowledge. Multimodality in this research refers to combination of architectural design knowledge, design factors, and visual information embodied within interactive models that can be manipulated. Two different approaches for representing design knowledge are discussed—library of data-referents and ontology-based model. Since these two approaches are complementary in nature, interaction between the two is explored.

Data-referent library contains interactive models, while the ontology represents architectural design knowledge. Ontology was used to develop a web-based application aimed to improve the decision-making process in schematic design. User evaluations have indicated that this is useful for information gathering and analysis, and that further development would benefit from inclusion of interactive three-dimensional models. Lastly, two different approaches for integration are discussed. The first method is through representation of metadata contained in the referents library through ontology, and the second method is the addition of referent models to the ontology structure.

## **2. Design Knowledge Representations**

### **2.1. Background**

Representations of architectural design have been evolving to reflect changes in building technology, materials, design practices and construction. Advancements in information technology allowed for novel representational methods, primarily CAD systems, three-dimensional modeling, and simulations of building performance. Currently, Building Information Modeling is the leading mode of design representation, where buildings are represented through a common database of building information and components. There is still a prospect for advancements and developments. Mainly, BIM is focused on representation of architectural product—building, and further development is needed to include representations of architectural knowledge in a way that they serve and enrich the design process.

### **2.2. Representations and Building Information Models**

Technological revolutions affect processes and products of architecture. Assessing the impact of information technology on architecture is challenging, since “we are still in the midst, if not at the very beginning of the revolution” [5]. Information technology has the potential to transform current design processes into a network of design, manufacturing, and management organizations where multiple professions are involved and geographic locations are insignificant. Understanding the future of architectural practice is even more challenging, since currently available computational tools are starting to change design processes, communication and fabrication. Especially difficult are the tools that have the ability to represent what was formerly obtained through education and practice, and the implicit values of architectural knowledge. Information-centric methodologies for design depend on computational representations of design processes, knowledge and elements.

Paradigm shift in architecture and construction industry has been originated by the BIM design and management methodology, where the primary elements are:

- Transfer in computer software techniques from procedural algorithmic programming languages to object-oriented; and
- Change in the building representation from drawings and written specifications to integrated models, taking building elements and spaces as the starting point.

BIM acts as an integrated building model which stores information contained in traditional building documents, such as drawings, specifications, and construction details, and much more, in a centralized or distributed database. Information management in this form changes the design procedure and documentation, since all the relevant information is organized as a database, rather than sets of drawings, specifications, etc. Data that resembles traditional documentation are specific views of common information. It virtually simulates design and construction, and provides groundwork for collaborative design, since all the relevant information about spatial organization, building components, and building systems is incorporated into building descriptions.

Visualization of design in three-dimensional space is one of the advantages of BIM; however, it is not the only capability and the integrative nature of contents must be emphasized. Beyond visualization, BIMs are used to review constructability issues where the construction team is able to analyze design decisions while in the early stages of the process and provide responses to the design team. Construction schedule can be integrated with the building model to visualize the sequencing of construction activities, which is also referred as “4D” modeling, since the time dimension is included. Cost estimation is another dimension, commonly referred as “5D”, since materials and components are analyzed and directly linked to cost databases to produce financial information and assist in analyzing design decisions as they relate to the economic factors.

The missing components of currently available modes of capturing information in BIMs are the design factors and knowledge used in the early stages of the design process to derive context-dependant architectural objects. The possibility for exploration of the conceptual space and precedent knowledge is also missing. This is the driver for the present effort for multimodal ontology-based knowledge representation of referents.

### 2.3. Explicit and Implicit Representations

Differences between explicit and implicit types of knowledge require innovative modes of capturing and structuring information. Explicit knowledge is easy to communicate, can be expressed alpha-numerically and can be stored on different media. Implicit knowledge, on the other hand, is difficult to communicate and formalize, and is usually accumulated through a learning process and practice. It can be “hidden” in a realization for whose creation this particular knowledge was used. We call these artifacts “referents” thus meaning architectural precedents, analogues and metaphors to which designers refer

during creative work. However, both explicit and implicit types of knowledge are utilized in the design process, and advanced computational applications should offer them to designers and support the transfer between these types.

## 2.4. Data Structures and the Need for Multimodal Representations

Computational environments that support structured innovation and adaptation require representations of implicit knowledge through information models. Over the years, three different categories have been proposed and used: physical, logical and conceptual models [6]. Physical information models express conventional data structures in terms of records, strings, arrays, lists, and are the most primitive forms. Logical information models consist of abstract mathematical symbols, such as sets, arrays and relations. Conceptual information models are the most expressive for modeling applications and structuring information bases, since they rely on abstraction mechanisms inspired by cognitive sciences and artificial intelligence.

A study of cognitive theories on mental representation of knowledge gave us valuable insights which could be used for computational approaches [1]. For example, category knowledge represents the fact that several representations share the same pattern. It has a *multimodal nature*. This means that a category exists, other than by its name and properties, by its picture, smell, sound, taste, action and touch. The question is how the brain integrates category's name and all other relevant information through different modalities. The structures through which category knowledge is represented, give us ideas about the ways in which referents can be approached in design situations. Four types of category structures are reported, the first two of which we find as directly linked to use of referents [7]:

- **Exemplars**, which are individual category members, are very strong at the recognition stage.
- **Rules**, which provide precise definition of the criteria for a category, are not the first to be used at recognition, but provide a much more stable basis for it. Different brain systems are used to represent exemplars and to represent rules.

These cognitive aspects give precious conclusions in relation to the description of referents containing design knowledge, namely, they should: (1) be represented in all possible formats of knowledge (imagery, features structure, amodal symbols); (2) provide relational (declarative) and procedural information (including its objective and actions structure); and (3) support the creation of exemplars, rules, prototypes and background knowledge in order to build a rich and stable category representation [1].

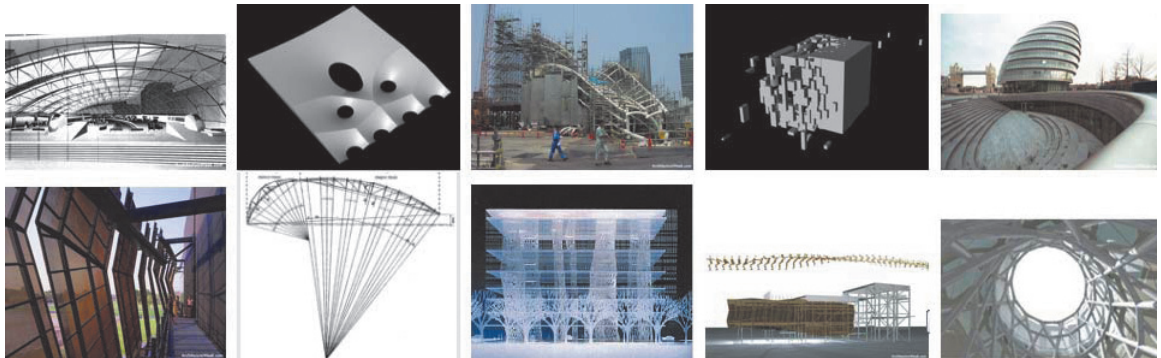
These considerations brought the idea of describing a referent (an outstanding building, for example) through chunks of knowledge embodied in it. Issued from the theory of the fragmented organization of memories, a chunk is a meaningful piece of information representing one aspect of an

object or phenomenon. This idea was already explored, taking in consideration Issue, Concept and Form aspects of a referent [8].

In order to be coherent with the above described multimodality, procedural knowledge is made available for the referents. It concerns the know-how, and can have different aspects: know-how used to create the object; or procedures by which the object can be transformed or manipulated. Some of the know-how may be represented by rules. This way, other than serving as a visual exemplar, a referent can facilitate the creation of rules and thus, enforce the category knowledge. In a digital representation of a referent, we can encode a rule by a parametric dependence, equation or an algorithm. The latter makes a process or a procedure explicit. By giving a name to the parameters, we introduce also propositional knowledge into the model. This way, the chunks of knowledge become interactive models of chunks of knowledge. They are intended to serve as referents playing important cognitive role during the process of design learning [9].

### 3. Design Knowledge Representations by Referants

Based on the already described cognitive aspects, design knowledge and know-how were embodied in referents represented in multimodal formats and structured in a library (Libre Archi) whose objective is to provide a possibility for design space exploration and design knowledge reuse during early stages of architectural design [2]. Multi-format representation consists of visual information, interactive model which can be manipulated alphanumerically or directly on the screen, text, video, etc.



▲ Figure 1. Visual representation of referents, general explorative view of Libre Archi

▼ Figure 2. Video snapshots: simulation of the formation effect of the wind.

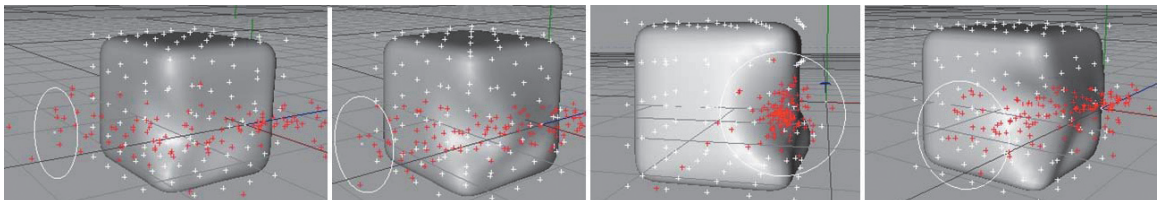


Figure 1 shows a general view of some visual representations of referents from the library. Figure 2 presents snapshots of a video explaining the formative effect of the wind (through a simulation using dynamic flow of particles).

Here is an example of the semantic description of a referent (train station), chosen to be part of the library because of its characteristic structure and its integration to the form of the site where an interactive generative model of the structure is available as well:

1. Generic information: *Description, Name of building, Place, Year, Architect/author, Function, More information (link on the Web)* – presented in Figure 11.
2. Architectural features (Can include structure, acoustics, visibility, climatic performance, energy optimization, materials, response to wind, sun and shadow, responds to site context, etc. Not all concepts are used but only the ones for which this referent was retained in the library.)
  - a. Structure (asymmetric form dictated by the site and the functionality – the train height); three-pin arch, with the centre pin moved to one side (allowing for the variation in height)
  - b. Responds to site context (asymmetric form dictated by the site and the functionality)
3. Digital features (of the interactive *chunk of knowledge*):
  - a. Modeling type: Generation;
  - b. Geometric description: Splines;
  - c. Algorithmic description: Links between objects;
  - d. Parametric distribution: Atom array and Data input;
  - e. Physical simulations: none

Design knowledge embodied in referents was proven to be most creatively used when internalized, but can assist the design process when transferred and adapted to a new context as well. Referents can offer advantages for design exploration and for design knowledge transfer [2].

The structure of this library is not perfect in terms of establishing links between referents and knowledge. That is why ontology is considered.

## 4. Ontologies as Knowledge-Based Models

### 4.1. Definitions of Ontologies and Use in Computational Models

Ontology is a knowledge-based representation of a certain domain, utilized to structure information and express relations between different concepts and elements contained in the model. It describes individuals as the basic objects, classes as collections or categories of objects, their properties and characteristics (individuals and classes), and relations between them.

One of the earliest definitions states that “an ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the



rules for combining terms and relations to define extensions to the vocabulary”, indicating the components, rules, and the inferred knowledge obtainable through ontology [10]. Generally accepted definition states that “ontologies are defined as a formal specification of a shared conceptualization” [11]. Conceptualization refers to an abstract modeling of a certain domain by identifying the associated concepts; formal indicates that the ontology structure should be machine-readable, and shared indicates that the represented knowledge should be common knowledge accepted by a group. There are numerous examples of ontologies developed for various domains and applications, such as general ontologies describing concepts of time and events, domain-specific ontologies describing mechanical components of a car or different structures of a protein, and also application ontologies. Architectural design consists of concepts that underlie the physical structure, and may be based on functional, cultural, and technological rules that guide the organization of elements. Therefore, knowledge-based representation should capture and represent range of concepts between the intention and the physical structure of a building. In that sense, systems that support creative reuse of existing knowledge should contain design factors and drivers, and following section outlines how ontology-based model of design factors has been developed.

## 4.2. Ontology Development Methods

Several methodologies for ontology development have been recognized [12], [13], [14], [15]. These differ depending on the type of ontology domain, and the type of associated problem or ontology scope. Methodology proposed by Uschold and King has been utilized for this work, where four general activities are performed during the development: identification of the purpose of the ontology, ontology building, evaluation and documentation [13]. Three strategies are suggested for identifying ontology contents:

- **Top-down approach**, where abstract concepts are identified first and gradually specialized into specific contents;
- **Bottom-up approach**, where most specific concepts are identified first and gradually generalized into abstract concepts; and
- **Middle-out approach**, where most important concepts are identified first and then generalized and specialized into other concepts.

Purpose of the ontology discussed in this work is to represent architectural knowledge, such as physical, environmental, and contextual characteristics influencing building design. *Protégé 2000* ontology editor has been utilized for ontology development, and the tool is described in [16] and [17]. Ontologies in general contain classes as concepts of a certain domain, instances as real examples of these concepts, and associated properties and relationships. The first step is the development of conceptual classes, and it

usually begins with identification of competency questions, which are utilized to scope the contents. Based on the above defined purpose, several questions were used to structure contents of the ontology, mainly:

- What are the design factors that influence design decisions?
- How is the architectural knowledge characterized?
- What are the relationships between buildings and design factors?
- What are the properties of existing buildings?
- What are the roles of different agents?
- How does an architect look and find information relevant to new and previous designs?

Responses to these questions initiated ontology development. The underlying assumption is that architectural design is not only based on inspiration, but also a rational process, where problems or issues are solved based on certain criteria, such as that choice of materials depends on economic, physical, and climatic characteristics. Ontology was constructed using a top-down approach, where upper classes are conceptual, and subsequent classes are specialized to respond to the above questions.

### 4.3. Contents and Main Classes

Main classes include *Agents*, *Building*, *Design\_Process*, *Design\_Factors*, and *System Considerations*. *Agents* class is intended to represent different roles in the process. *Building* class represents building as a physical object, where associated properties are used to describe its characteristics, such as the location, height, surrounding area and the environment, structural system type, materials, spaces, elements, etc. *Design\_Process* describes sequences in the process, and roles of different agents during these discrete points. *Design\_Factors* is the major component of the ontology, with the largest number of sub-classes and properties assigned to this particular part. Environmental, physical, economic, socio-cultural, geometric, and technical aspects are described within the *Design\_Factors* class. *System Considerations* class consists of metadata relations between *Design\_Factors* and *Building*, where types of design factors are associated with higher-level design considerations, such as sustainable design, building envelope design, economic and socio-cultural considerations.

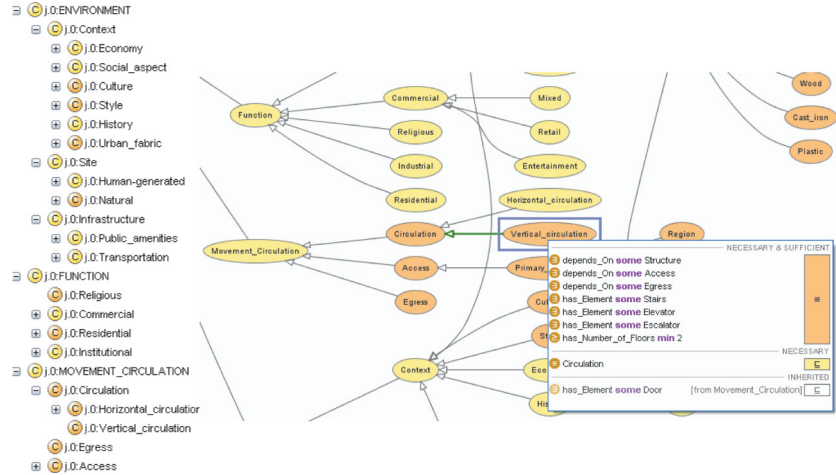
Properties are utilized to assign specific characteristics to classes. Two general types of properties are used: object properties and data-type properties. Instances are used to populate ontology contents with actual data. Object properties are used to describe properties of classes and are inherited by instance data that belong to a particular class. Data-type properties are utilized to assign numerical values for instance data.

### 4.4. Restrictions and Rules

Classes within the ontology are further defined using restrictions, which are logical statements used as connectors between different parts of the

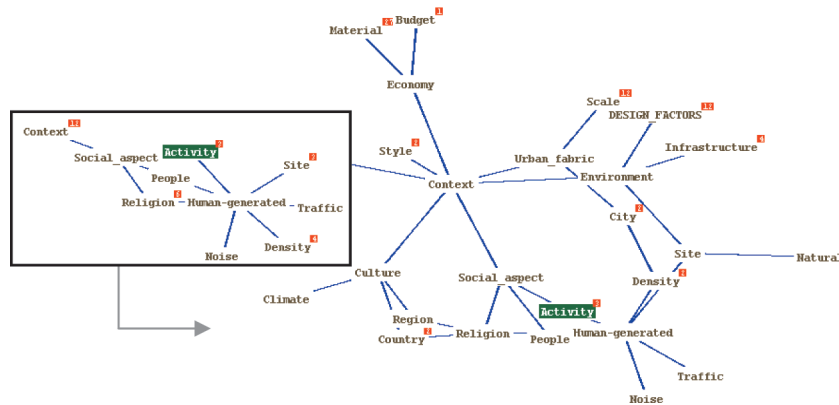
ontology. Existential restrictions are used to describe a class or instances of a class that have at least one kind of relationship to another class. Universal restrictions describe the classes that only have relationships to other classes or individuals of a class. Cardinality restrictions specify the number of relationships. Value restrictions are used for a specific data-type. Further, restrictions can be asserted for complex classes, such as union, intersection, or complements of other classes.

► Figure 3. Partial ontology class structure and relationships



Combination of classes, instances, declared properties and restrictions make up the structure of the ontology. For example, Figure 3 portrays the portion of contents of *Design\_Factors* class, where relationships between building circulation and other ontology contents are constructed through existential restrictions. Restrictions associated with *Vertical\_circulation* portray that this design aspect depends on the structural system, types and location of access and egress, types of building elements, and the minimum number of floors.

Practical utilization of the developed ontology is aimed for design reasoning and support, and there are several ways in which information can be explored. Reasoning support is one of the major advantages of representations of human knowledge through ontologies, and structured methodologies for information search. Ability to build complex queries is achievable, as well as graphical search. Figure 4 presents one possible approach, in particular searching for types of activities and how they relate to building design. The depicted methodology is bottom-up, where the initial start is from the lower level of the ontology. As the radius of influence is expanded, the relations with other factors are revealed, where dynamic update of instance data is also shown. The end result is more comprehensive than the initial start and offers a broader perspective of the influence of activities on the design. This approach would be beneficial because relationships between certain design factors and the overall design are explicitly portrayed, and can be visually examined.



◀ Figure 4. Graphical representation of relations between ontology contents

## 5. Implementation and Evaluation

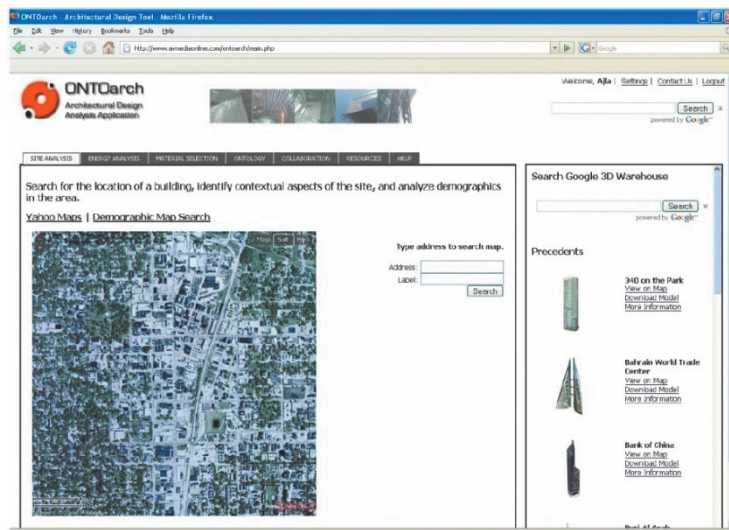
### 5.1. Need for Knowledge-Based Applications

The development and use of knowledge management tools for architecture and construction has overlapping phases, depending on aspirations and flexibility. The first step aims to improve traditional design by developing collaborative applications via internet portals for universal access to traditional design documentation [18]. However, the design process is not affected by these implementations; rather the communication system between agents is improved. The second approach is the model-based design, which is currently gaining popularity. In this case, modeling is based on the building components, but the process uses traditional project documentation where the representations of building design are still achieved by geometrical orthogonal projections and floor plans. The next step is the overall model-based design and construction, which aims to integrate design in the whole sector, from the initial schematic design, through all design phases and construction [19].

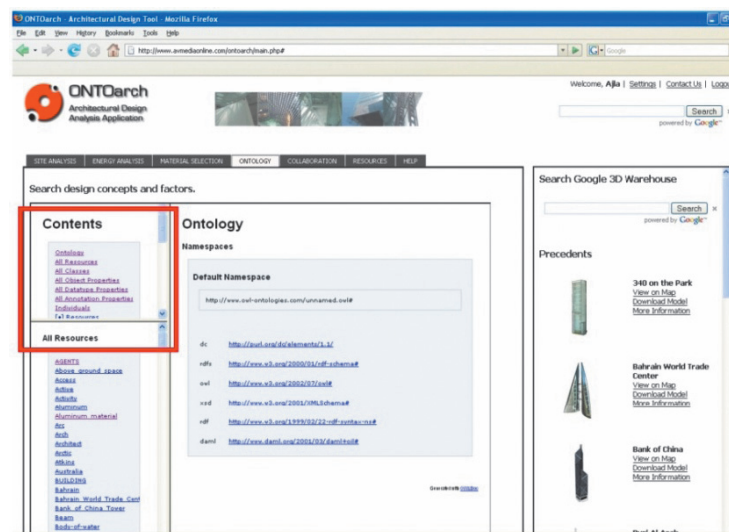
### 5.2. Implementation of Ontology in a Web-Based Application

The developed knowledge-based model of design factors has been utilized to design and construct a web-based application referred herein as ONTOarch, shown in Figure 5. It was designed and developed as an educational tool in order to facilitate understanding of systems integration and factors that influence building design, as well as sustainable design practices, and it is aimed for early schematic design and exploration of concepts. The objective was to develop an interface which utilizes ontology for early-phase schematic design. Ontology is primarily used for indexing, aimed to present information to its users, and improve the decision-making process in design [3]. Ontology represents architectural design factors in a semantic model, as seen in Figure 6. It is also linked to the precedents, displaying information for existing buildings, as seen in Figure 7. The frames allow navigation of classes, individuals and properties, presenting relationships between all contents of ontology.

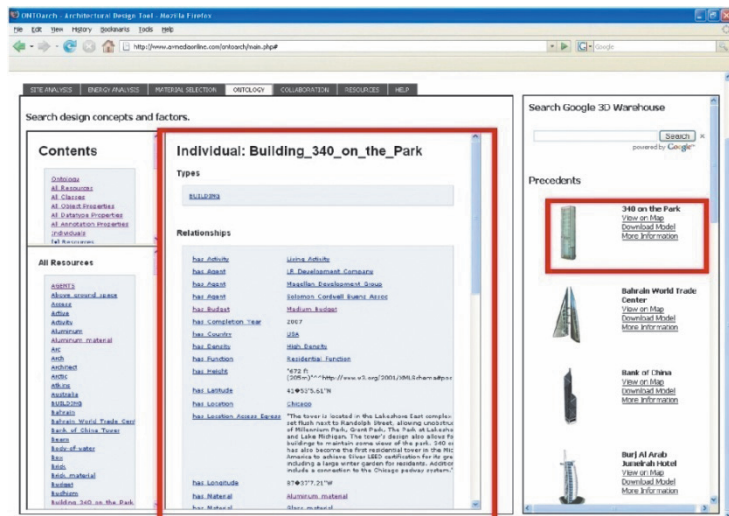
► Figure 5. Implementation of ontology for knowledge representation in a web-based application



► Figure 6. Ontology classes in a web-based application



► Figure 7. Building information displayed through ontology



Initial goal for application development was to provide an interface to act as a web-based integrated desktop, where the majority of information needed can be easily accessed, and users can refer to the ontology for exploration. Several functionalities were planned, such as providing capabilities for site analysis, materials selection and collaboration.

Application development consisted of these following stages:

- Determination of application scope stated above
- Contextual inquiry
- Development of low-fidelity prototype
- Testing of low-fidelity prototype through cognitive walkthrough and heuristic evaluation
- Development of a functional prototype
- Initial user evaluations of functional prototype
- Implementation of user evaluation results into final development stage
- Secondary user evaluation.

### 5.3. Application Content

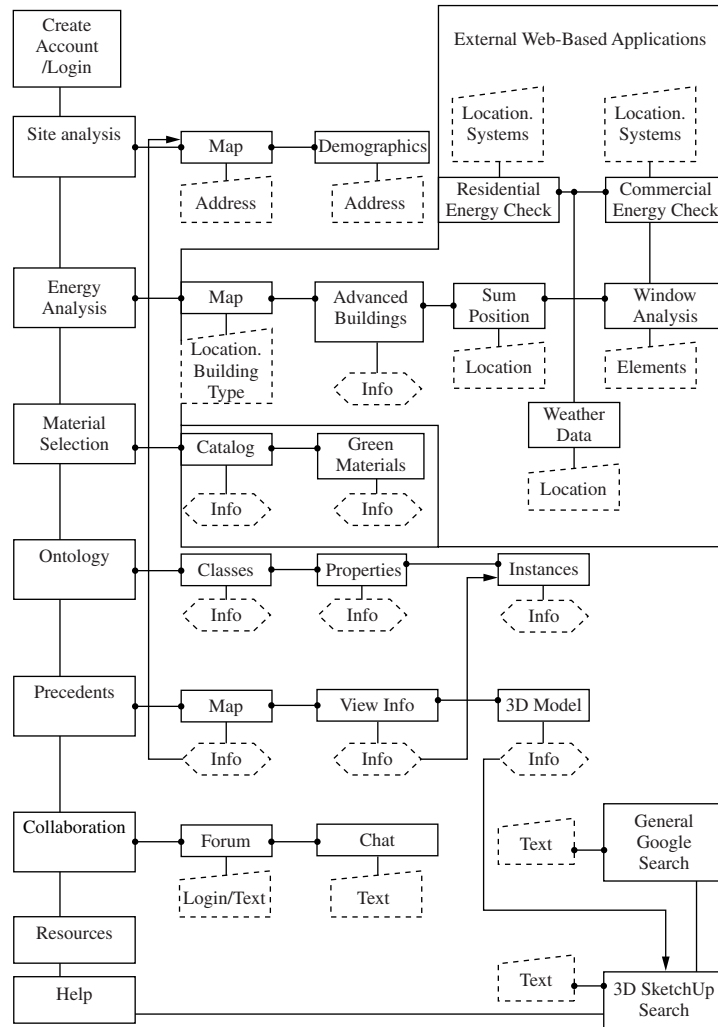
Implementation of the ontology in the web-based application required multiple programming languages and toolkits. The base of the code is Hypertext Markup Language (HTML) and most of the style is in Cascading Style Sheets (CSS). The dynamic functionality was incorporated using JavaScript. The user data is stored in MySQL database and login verification is made through PHP. The final functionalities of the application include site analysis, energy analysis, material selection, collaboration, ontology exploration, precedent database of existing buildings, general web-based search, and web-search of existing 3D models. The structure of ONTOarch is shown in Figure 8, as well as required input.

Components of the site analysis include a map with geographical and satellite information, as well as demographic information and census map. Geographical mapping requires an address or location for input, and is able to search worldwide locations. Census map requires an address and zip code for US Census Data, and searches for population and housing information according to a 1 mile, 3 mile or 5 mile radius of the input location. Energy analysis components are external web-based applications, such as MIT Design Advisor, Sun Position Calculator, Window Analysis, Commercial and Residential Energy Code Compliance Check, and Weather Data. These applications require input such as location, functional type, and types of components. Materials selection consists of Sweets Catalog and sustainable materials databases. These applications are launched externally and can be searched for products, manufacturers, CAD details, and 3D models.

Ontology presents terms and concepts relating to architectural building design knowledge, and it represents architectural design factors in a semantic model. It is also linked to the precedents, displaying information for existing buildings. The frames allow navigation of classes, instances and

properties, presenting the context and relationships. Following the development of the fully functional ONTOarch application, several evaluations were conducted in order to study organization, functionality and effectiveness of this application.

► Figure 8. Structure of ONTOarch and user input



## 5.4. User Evaluations

Initial user evaluation consisted of in-depth observation, survey, and interviews in an educational setting. Five graduate architecture students performed the evaluation simultaneously, where they were given sets of detailed tasks to perform for each aspect of the application. Evaluation was performed for approximately 45 minutes, with additional 15 for survey completion. Interviews lasted about 20 minutes. The survey contained questions regarding functionality, content, and organization of the application, based on differential seven-point scale, as well as open-ended



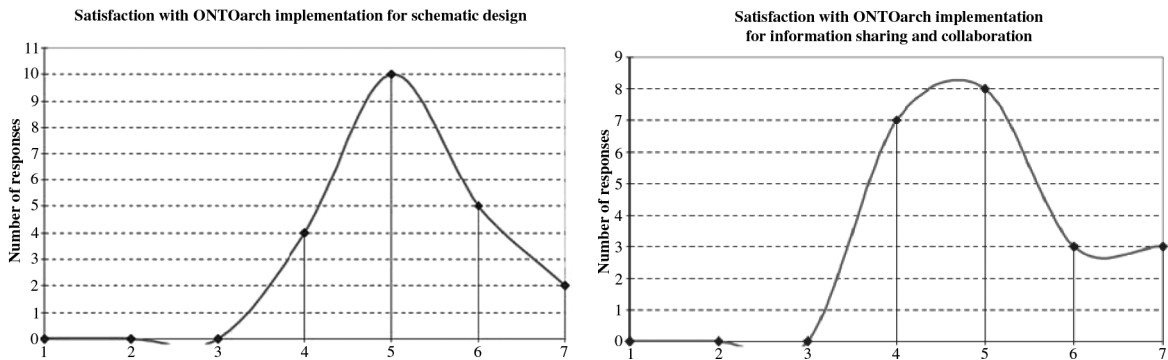
questions reserved for comments. This initial user evaluation was aimed at discovering usability issues. Some of the responses proved to be critical for improving the contents and organization, such as addition of “Help” sections to provide an overview and a user guide for the application. Following the final development stage, second user evaluation was performed.

Second user evaluation was also conducted in an architectural studio setting, and it involved twenty one students. The studio was comprised of mixed undergraduate and graduate students. The study was similar to the initial user evaluation, where students were given the set of tasks to complete, access to the web-based application and a survey. The study consisted of observations and survey. Once students were given overview of the application and the set of tasks to complete. Selected tasks are described below:

- **Access:** Can you create accounts and log in? Does the application provide feedback for registering?
- **Site analysis:** You will be able to view maps to understand the site context. Can you locate location and label search box? Does the map respond to the search?
- **Energy performance:** You will be able to view specific information about energy performance and perform external simulations. The applications are MIT Design Advisor, Sun Position Calculator, Window Analysis, Commercial and Residential Energy Code Compliance Check, and Weather Data. Can you access these applications? Do you understand the text explaining the functionality of these applications?
- **Material selection:** You will be able to view specific product information (Sweets Catalog) and sustainable materials database. These are external applications. Can you access them? Do you understand the text explaining the content?
- **Ontology:** You will be able to view and navigate ontology, which presents terms and concepts relating to architectural building design. Are you able to navigate? Do you receive information that helps making design decisions?
- **Collaboration:** You will be able to communicate through a forum and real time chat. Can you post topics to the forum? Can you view other posts? Can you interact with other users who are currently online?
- **Precedents:** You will be able to view buildings included in the precedents list, which are also part of the ontology with declared data. You can view the location of buildings on the map, download models, and receive information about these buildings from ontology. Are the functions working (locating on the map, viewing the model, and getting more information)?
- **Modeling:** You will be able to view precedents’ building models (SketchUp) and search for other models through Google 3D Warehouse. Are these functions working?
- **Search:** You will be able to perform general web search. Are the results visible?



Once the students completed these tasks, they completed the survey by rating the contents using a seven-point Likert scale. Rating 1 represented “Poor” grading and rating 7 represented “Excellent” grading. The survey questions asked users to rate the contents of the application, and to identify whether the application is helpful in providing information necessary for schematic design, collaboration and information sharing, and whether they would use it for future projects. Results indicated that users were satisfied with the implementation for schematic design, information sharing and collaboration, as seen in Figure 9.

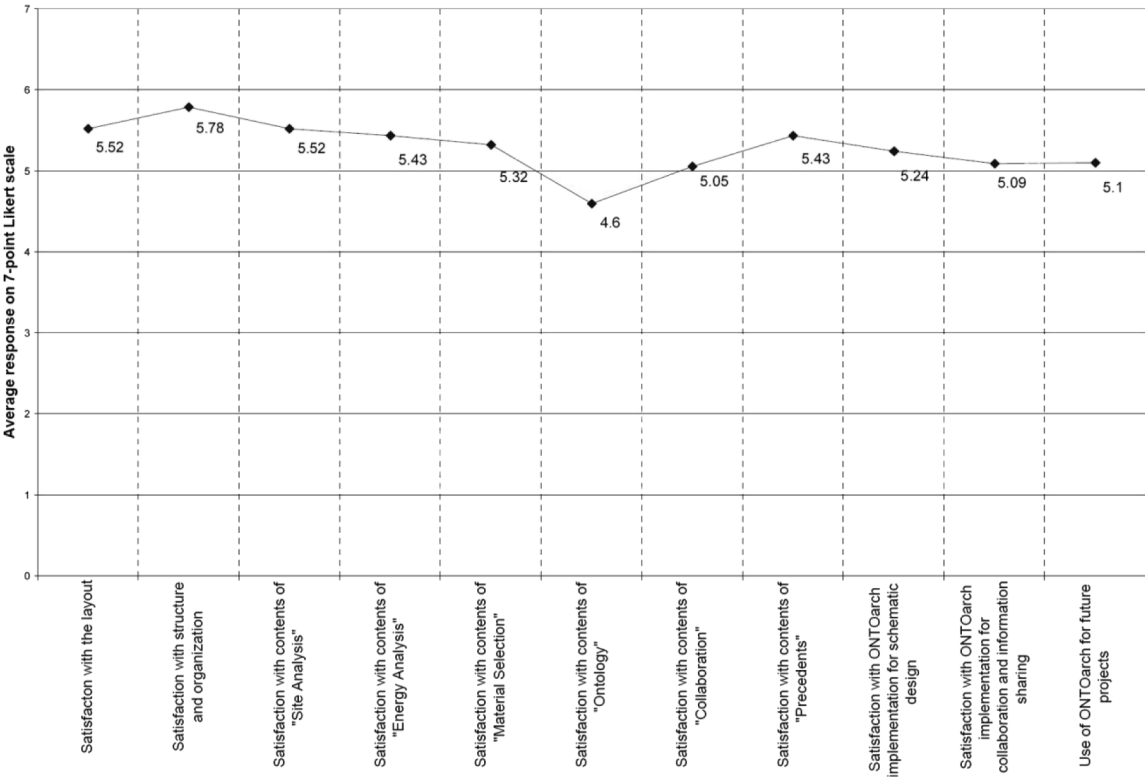


▲ Figure 9. Results of the survey

- a) Responses for satisfaction with implementation for schematic design;
- b) Responses for information sharing and collaboration

Figure 10 shows the results for specific application components. The scores range from 5.52 (site analysis component) to 4.6 (ontology components). Highest scores are observable for site analysis, precedents and energy analysis (5.43), material selection (5.32), and gradually decrease for collaboration (5.05) and ontology (4.6). Also, the highest standard deviation was attained for ontology and precedents components, indicating that the scores had higher ranges. Possible reason why the higher-scored components received such scores is that users preferred that these actions were combined in one interface. Possible cause why ontology component received lowest score is that the graphical representation of ontology was not user friendly. Ontology components were not structured in a tree-like manner, but rather alphabetically sorted according to the type, such as classes, object properties, datatype properties, and instances. The reason for this particular structure is that OWL ontology language (original ontology structure) had to be converted into standard HTML format to be included in the web-based application; therefore the content could not be displayed as ontology, but rather as a taxonomy. Another drawback is that ontology was static, and could not be updated by users. In order to achieve this, users would have to use ontology editor tool, such as Protégé 2000. This aspect negated the main advantage of ontologies. Users expressed satisfaction with implementation of ONTOarch for schematic design, where average score is 5.24. Also satisfaction with implementation for collaboration and information sharing received high score of 5.09. Users indicated that

they would most likely use this application for future projects, with score of 5.1. The overall results are satisfactory and consistent, indicating that this application would be a valuable tool for assisting the decision-making process in schematic design. In order to address the aspects that received lower ratings and scores, integration with data referents and multimodal representations are explored. Since within this application users could not modify the contents of the ontology, or precedent models to apply similar knowledge to a new problem, integration with visual interactive models is explored.



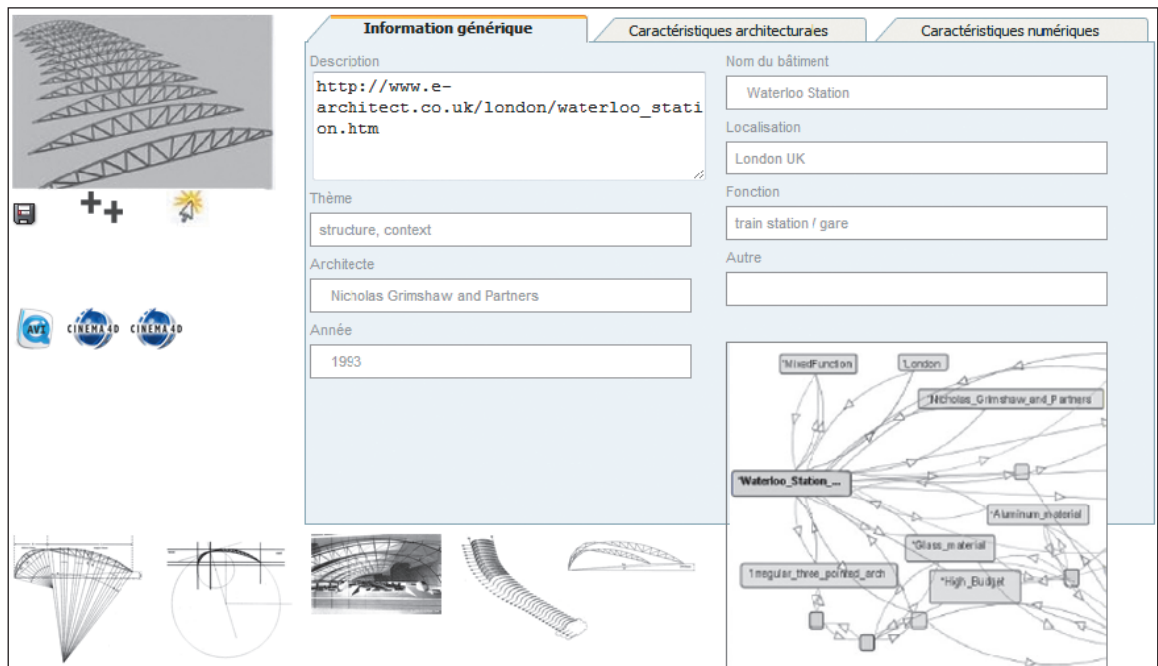
## 6. Integration Methodologies for Multimodal Representations and Prototype

Integrating referents library of 3D models and ontology to describe architectural objects provides a more thorough understanding and gives the possibility for an interactive and creative exploration of both relations (from the ontology) and know-how (from the interactive models). Thus, multimodal representations of architectural knowledge are utilized, where conceptual knowledge model is used to express architectural knowledge explicitly and three-dimensional interactive models to express visual characteristics and implicit know-how. Ontology structure contains aspects of architectural design knowledge and information about specific examples,

▲ Figure 10. Summary of survey results

while interactive referents contain visual and procedural properties. The ontological model is based on capturing design factors and drivers, therefore explicit meaning is associated with pieces of information that can be used and adapted to suit the needs of a design problem. Modeled referents contain “chunks of knowledge”, and are associated with examples of real buildings or methods of creation, and context-based usage through ontology. These three-dimensional pieces of information can be manipulated in existing CAAD modeling programs and modified, adapted and combined according to specific design criteria.

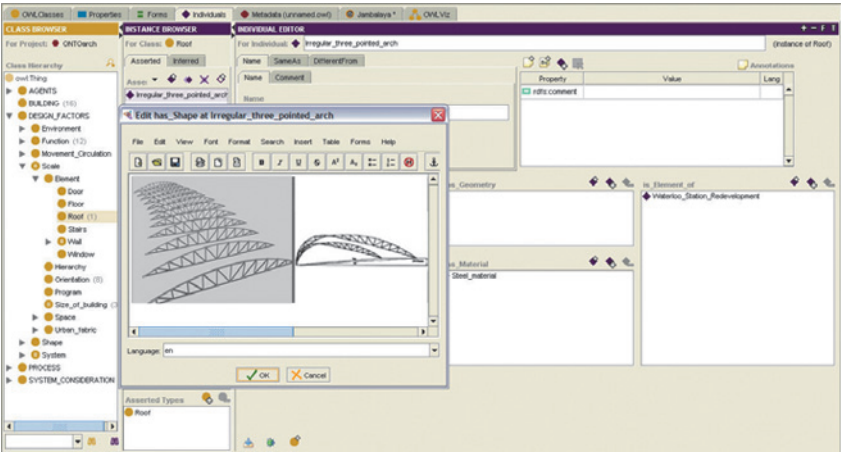
Since the nature of the information and knowledge contained in ontology and referents library are distinctive and complementary, there are essentially two methodologies for integration of the two systems which were explored: on the basis of the interactive referents library; and into the ontological structure. The first method is representation of metadata contained in the interactive-referents library by populating contents of the ontology that relate to the embedded knowledge, as seen in Figure 11. Second method is addition of referent models to the ontology structure, and population of necessary information fields to reflect the meaning, contents and relationships between “chunks of knowledge” contained in the



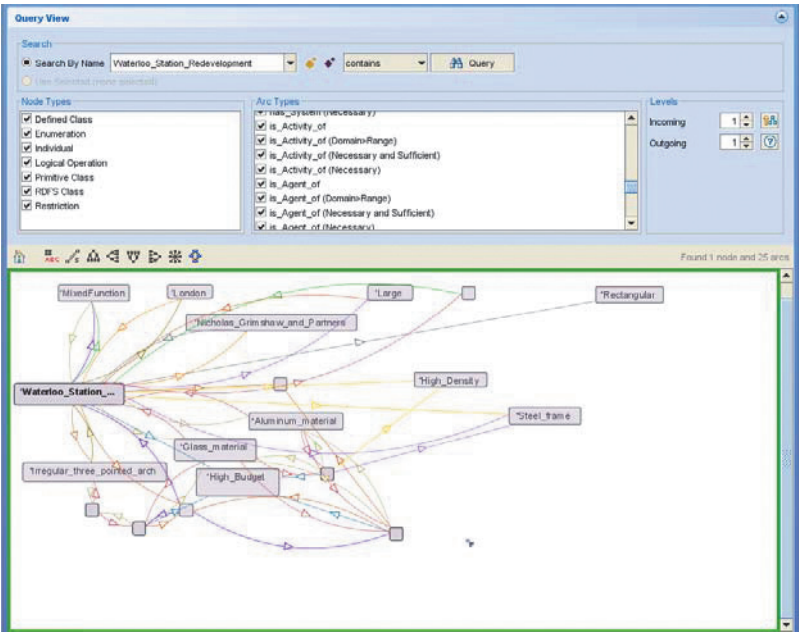
▲ Figure 11. Integration based on the library of interactive referents (Libre Archi) [20]

referents. Both methodologies have their benefits and drawbacks. In the first case, benefits are that existing interactive three-dimensional models are described using contents of the ontology, and direct access for modification of models is possible. An overall view to the visual representations of the referents is possible at a glance, because of the simple web-page structure.

Drawbacks are that only partial contents of the ontology are utilized to express metadata, therefore higher level and relations are not explicitly defined. In the latter case, “chunks of knowledge” are described utilizing contents of the ontology, and the relationships between the elements and the rest of the contents are explicitly defined or inferred from ontology contents. For example, Figure 12 shows properties of an element, and the relation to a particular building. Ontology structure is utilized to relate properties and values of different types of information, and can be used to form queries, as seen in Figure 13. However, interactive models cannot be modified directly from the ontology, but rather have to be isolated and modified using modeling applications.



◀ Figure 12. “Chunks of knowledge” utilized to express properties of an element



◀ Figure 13. Query for relationships between “chunks of knowledge”

Further development should focus on integrated functional prototype that combines benefits of both methods and elimination of drawbacks. Moreover, integration with existing digital systems via web-based application should be explored, since dynamic access to information and knowledge is preferred.

## 7. Conclusion

Virtual building and Building Information Modeling (BIM) are being increasingly used in architectural design practice. These methods consider building as a common database of information, allowing for comprehensive representation, analysis, and information processing. The missing components of currently available modes of capturing design information are the design factors and architectural design knowledge, and relationships between explicit and implicit knowledge. This article discussed research on the multimodal representations as a method to overcome this challenge. Multimodal representations of architectural design knowledge have been investigated through referents library of three-dimensional models and ontological representation of design knowledge. Referents library contains interactive models of “chunks of knowledge” utilized in architectural design, and ontology represents relations between the design factors. Ontology was used to develop a web-based application, aimed to foster exploration of integrated design factors and improve decision-making process. User evaluations have shown that this application would be a valuable tool for schematic design, and in order to improve the capabilities and functioning, integration with visual three-dimensional interactive models would be advantageous. Benefit of the combinatory representation is that implicit and explicit types of knowledge are integrated, where visual, numeric and procedural information is embedded, as well as design rules. Interactive search and query, based on design rules and architectural knowledge, and parametric variation of the model based on the information received from ontology are the advantages that can improve current practices.

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