3DIR: Exploiting Topological Relationships in Three-Dimensional Information Retrieval from BIM Environments

Peter Demian[1], Kirti Ruikar[2], Tarun Sahu[3], Anne Morris[4]

1) Senior Lecturer, School of Civil & Building Engineering, Loughborough University, UK. Email: P.Demian@lboro.ac.uk
2) Senior Lecturer, School of Civil & Building Engineering, Loughborough University, UK. Email: K.D.Ruikar@lboro.ac.uk
3) Undergraduate, IIT Guwahati, India. Email: tarun.sahu@iitg.ernet.in
4) Emeritus Professor, Centre for Information Management, Loughborough University, UK. Email: A.Morris@lboro.ac.uk

Abstract:

An increasing amount of information is being packed into Building Information Models, with the 3D geometrical model serving as the central index leading to other building information. The Three-Dimensional Information Retrieval (3DIR) project investigates information retrieval from such environments, where information or documents are linked to a 3D artefact. Here, the 3D visualization/geometry can be exploited when formulating information retrieval queries, computing the relevance of information items to the query, or visualizing search results.

Following reviews of literature in BIM and information retrieval, a clear gap was identified in the practice of information retrieval from BIM systems. The practical need for such a system was further specified using workshops with construction professionals as end users. A software prototype was developed, built on a commercial BIM platform. The 3DIR prototype creates an index of all text attached to the 3D model. The user can search for information by selecting specific 3D objects, specifying a spherical volume of the model and/or entering search keywords.

This paper focuses on the exploitation of model topology. Relationships between 3D objects are used to widen the search, whereby relevant information items linked to a *related* 3D object (rather than information linked directly to a 3D object *selected* by the user) are still retrieved but ranked lower. Several such relationships between 3D objects were tested, whether explicitly encoded in the BIM information architecture or inferred from geometrical computations. An evaluation of the software prototype which exploits such topological relationships demonstrates its effectiveness but highlights the challenges to software users of added complexity. The system is subjectively rated comparably favorably. It is concluded that care needs to be taken when exploiting topological relationships, but that a tight coupling between text-based retrieval and the 3D model is generally effective in information retrieval from 3D BIM environments.

Keywords: Information retrieval, Document management, Building Information Modelling, BIM, 3D models.

1. INTRODUCTION (ALL CAPITAL, 10 PT., BOLD, TIMES NEW ROMAN)

In building modelling environments, more and more information is being crammed into 2D/3D building and product models. This is particularly true given the rise of Building Information Modelling (BIM, Eastman et al., 2011). The Three-Dimensional Information Retrieval (3DIR) project investigates information retrieval from these environments, where information or documents are linked to a 3D building model. In these situations, the 3D visualization or 3D geometry of the building can be exploited when formulating information retrieval queries, computing the relevance of information items to the query, or visualizing search results. Managing such building information repositories in this way would take advantage of human strengths in vision, spatial cognition and visual memory (Lansdale and Edmonds, 1992; Robertson et al., 1998).

Information retrieval is associated with documents, and a critic might argue that documents are relics from the pre-BIM age that are no longer relevant in the era of BIM. However, the challenge of information retrieval is pertinent whether we are dealing with documents which are coarse grains of information or building object parameters/attributes as finer grains of information. Demian and Fruchter (2005) demonstrated that traditional retrieval computations can be applied with good results to 3D building models where textual or symbolic data are treated as very short documents.

This paper describes the findings of the 3DIR project whose latest aim was to develop an information retrieval toolset for documents/information linked to 3D building models *which leverages topological relationships in the 3D model*. This aim was achieved through the following objectives:

- To review the applicable techniques from the fields of BIM, information retrieval and information visualization, particularly those techniques which exploit topological relationships in the 3D model.
- To identify specific topological relationships which exist in current BIM information architectures and

which can be exploited usefully for information retrieval.

- To extend the 3DIR software system to use such topological relationships and to evaluate the improved 3DIR, thereby validating the proposed theoretical exploitation of 3D model topology.

2. RELATED WORK

Building design, construction and operation are information intensive activities. Several researchers (Leslie, 1996; Veeramani and Russell, 2000; Ugwu, 2005) have reported the problem of "information overload" in the construction sector.

Information retrieval techniques have been used in construction to retrieve reusable designs (Demian and Fruchter, 2005). Beyond text, Brilakis and Soibelman (2008) automatically identify particular features in construction site photographs with a view subsequently to using information retrieval techniques to manage collections of photographs. Bridging textual and geometric content, Caldas et al. (2002) propose techniques for automatically classifying construction documents based on project CAD (Computer Aided Design) components. Lin and Soibelman (2009) augment standard information retrieval techniques with formal representations of domain knowledge to improve the performance of a search engine for online product information. Rezgui (2006) similarly uses domain knowledge to formulate an ontology that informs the indexing and retrieval of construction content.

None of the studies encountered specifically exploited 3D BIM model topology for information retrieval. This approach lies at the intersection of three fields: (1) BIM and CAD, (2) information retrieval, and (3) model topology.

2.1 BIM and CAD

The state of the art in digital content management in building design and construction projects is being transformed by the emergence of Building Information Modelling (Eastman et al., 2011). Whereas CAD models classically modelled the geometry of buildings or building components in two or three dimensions, Building Information Models attempt to model non-geometric content as well. This content includes the non-geometric attributes of physical building components (such as the cost of a component) as well as non-geometric entities. For example, Building Information Models can include entities to model the processes of design (Austin et al., 2000) and construction (Koo and Fischer, 2000) and the organizations (i.e., teams and individuals) that execute those processes (Kunz et al., 1998). The focus of this paper is the non-geometric modelling of relationships between 3D objects in the model, here referred to as *model topology* (section 2.3).

In the context of the 3DIR project, it is noteworthy that, although as noted above, CAD and BIM models nowadays include both geometric and non-geometric information, the geometric 3D model of the building is central, and is expected to serve as a visual index that leads to the additional non-geometric content. This approach often fails because such systems do not exploit human abilities in spatial cognition and visual memory. Non-geometric content does not leave enough *information scent* (Pirolli and Card, 1999) in the geometric 3D model that enables the *information forager* to find it.

2.2 Information Retrieval

Information retrieval (IR) is concerned with systems that help users to fulfil their information needs, in particular computations to quantify the relevance of information items based on user queries. Demian and Fruchter (2005) demonstrated that traditional IR techniques could be applied to retrieve information from Building Information Models and product models; the semantic information attached to 3D objects could be treated as very short documents and standard text document computations employed, giving reasonable retrieval results. As noted in the introduction to section 2 and in section 2.1, information retrieval has recently been applied in managing the vast volume of information accumulated in building design, construction and operation.

2.3 Modelling of Topology in Buildings

In general language, *topology* is the "study of the way in which constituent parts are interrelated or arranged" (Oxford English Dictionary). In mathematics, topology is the study of a collection of open sets, making a given set a *topological space* (Gemignani, 1972). In spatial modelling, topology is concerned with the notions of "interior", "boundary", or "exterior". Paul (2009) examined how these notions could be captured by the Industry Foundation Class, as buildings were modelled in 3D Euclidean space. Borrmann and Rank (2009a) present algorithms for the standard topological operators in 3D space: *within*, *contain*, *touch*, *overlap*, *disjoint* and *equal*; their prototype uses IFC-VRML files.

In this research, *topological prelateships* are taken to include any relationships between 3D building elements in a model which may enhance information retrieval. These relationships might be strictly topological and concerned with interior/boundary/exterior of 3D components as noted above, more general spatial/directional

relationships (Borrmann and Rank, 2009b), or even relationships as they occur in a very general semantic sense, albeit linked to spatial topology (Lin, 2013). In this sense, any two objects in a model sharing the same attribute (for example: two components supplied by the same manufacturer) can be said to be related. If a user searching for information is interested in the first object, but not the second object related to it, information from the second object can still be retrieved but ranked as less relevant.

The literature reviewed in section 2 signposts the promise of systematically applying IR techniques in BIM environments, and highlights the unexplored potential of exploiting topological relationships between objects to improve information retrieval from building models.

3. METHOD

Following reviews of literature as presented in section 2, a clear gap was identified in the practice of retrieving information from BIM/CAD systems. To inform the design of a system to address this gap, workshops were convened at a large multinational contractor and a renowned architectural practice in London. A software prototype was designed and developed as an add-in under the Autodesk Revit BIM platform. Although the ultimate aspiration is for any software development to remain platform independent and avoid favoring any particular commercial BIM environment, it was found that the Autodesk Revit Application Programming Interface (API) provided excellent opportunities for development and research prototyping. The interface and system architecture of the 3DIR system are described in the Results section, section 4.1. This *original version* of 3DIR was evaluated with the help of professionals from contractor and architecture practices. The exploitation of topological relationships was tested using three particular relationships as a proof of concept:

1. The *hosted by* relationship. This is built in to the Revit information architecture; for example, a particular window may be hosted by a particular wall.
2. The *intersecting* relationship. For example, if 3D volumes are used to model spaces, the volumes for two crossing corridors would intersect one another.
3. The *touching* relationship. For example, two adjacent walls may touch one another.

The *intersecting* and *touching* relationships were able to be inferred using simple geometrical computations through the Revit API. Implementation of this exploitation of topological relationships is described in section 4.2. This *modified version* of 3DIR was re-evaluated with the help of a cohort of postgraduate students at Loughborough University. The results of the evaluation of the *original* (3DIR) and *modified* (3DIR+Topology) versions of 3DIR are presented in section 4.3.

4. RESULTS

4.1 3DIR User Interface

3DIR is developed as an add-in to Revit, and therefore (once installed) appears in the add-ins ribbon of the standard Revit interface. The 3DIR toolbar consists of three tools: Index, Search and About. The first step when searching a building model using 3DIR for the first time is to “index” the model using that icon on the 3DIR toolbar. This will create an index of all text terms from 3D object parameters or linked text documents. Once an index has been created, the “Search” tool can be used which brings up the dialogue box shown in Figure 1.

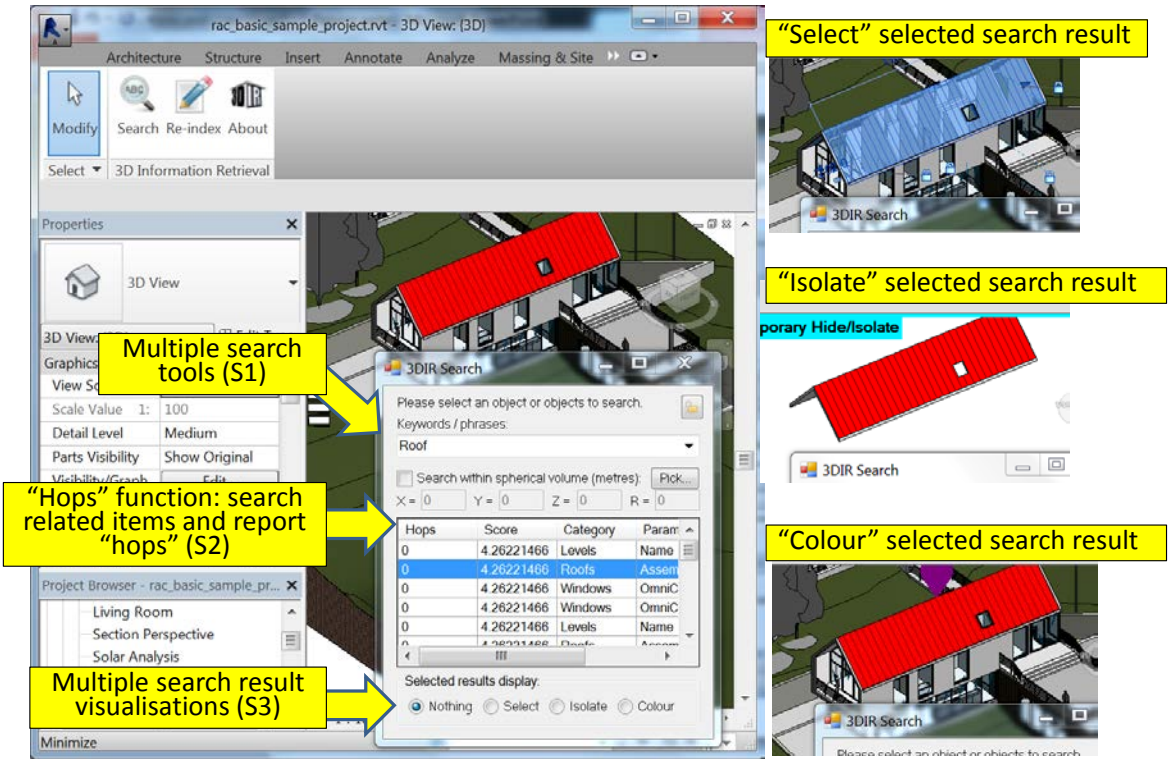

Figure 1. The 3DIR interface. Left: Screenshots showing the software functions satisfying the specifications (S) which emerged from the user workshops. Right: Various presentations of search results.

As the user enters keywords in the text box, search results are listed in real time in the dialogue box. In the example shown in Figure 1, the keyword "roof" is entered and search results listed related to the roof of the model. The search can be processed either on the whole building model if nothing is selected, or limited to the selected objects. As the object selection in the model changes, the search results are updated dynamically. The user is also able to limit the search to a spherical volume. Selecting a search hit from the list (e.g. the "Roof Assembly" item) will optionally "select" (or highlight) the Revit element containing that search term (i.e. the red roof graphic from the model), "isolate" it (i.e. temporarily hide all other items in the model) or identify the object by displaying a colored balloon next to it in the model. The size and color of the balloon can be used to denote various attributes, such as the relevance or type of information. Figure 1 shows an example search for "roof". The three options for displaying the selected search result(s) appear on the right hand side of the figure.

4.2 Exploitation of Model Topology in 3DIR

In order to establish relationships between the 3D building elements in the model, a separate list of other objects *hosting*, *touching* or *intersecting* each element in question is saved as a list of "Neighbors". While indexing, these Neighbors lists are indexed with their respective objects along with the object's other parameters. For each element, only one list of nearest neighbors is stored, i.e. one "hop" away. Subsequent neighbors, more than one hop away, are retrieved during the search, using a recursive function.

When searching a selected set of objects, the results are shown in the same way as when searching the whole building model. Selected objects containing the search keyword in any of their parameters are shown first in the results table with "Hops" value 0. Next, the list of neighbors of each of the retrieved objects is also searched. Neighboring objects containing the required keyword are listed in the results table with "Hops" value 1. The search is repeated recursively on the newly retrieved objects, each time incrementing the "Hops" value. This continues until the maximum number of Hops specified by the user. In this way, objects which are not in direct consideration but are related to the objects of the user's interest can still be retrieved but with less relevance.

4.3 Results of 3DIR Evaluation

Both the *original* (3DIR) and *modified* (3DIR+Topology) versions of 3DIR were evaluated by demonstrating the software to users and recording their feedback using a questionnaire. The samples of test subjects were drawn from different populations. 3DIR was evaluated by professional architects and builders: three professionals from the 3DIR project industry partners with over ten years of industrial experience. 3DIR+Topology was

evaluated by a sample of postgraduate construction students from Loughborough University (11 students with an average of 1.95 years of industrial experience). The questionnaire was based on the System Usability Scale (SUS, Brooke, 1996). Two additional questions were posed for 3DIR+Topology to gauge its recall and performance in averting information overload. The results are shown in Figure 2.

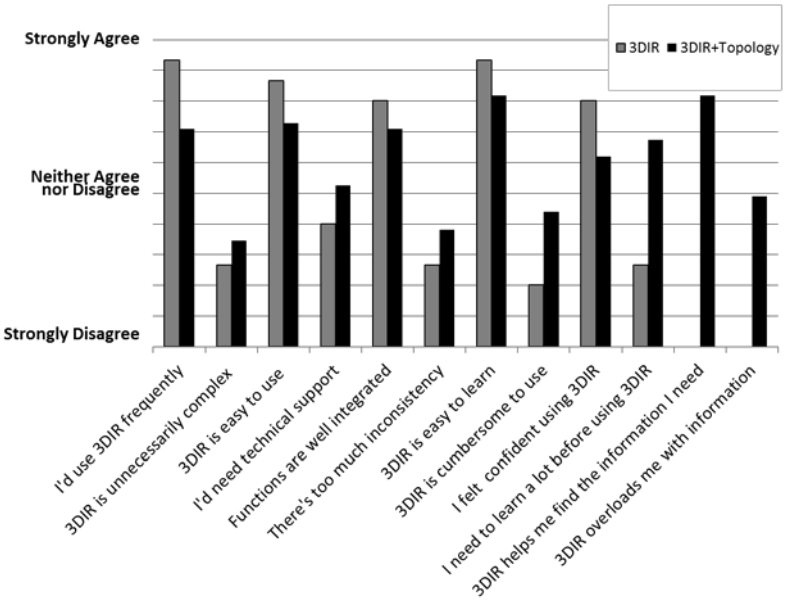

Figure 2. A comparison of the evaluation results from the original version of 3DIR and the modified version of 3DIR (3DIR+Topology). The questions are loosely based on the System Usability Scale (Brooke 1996) with three additional Likert questions for the modified version of 3DIR.

It can be seen from Figure 2 that although 3DIR+Topology was generally well received, without exception the new topology feature caused test subjects *to agree less strongly with the positive statements* and *disagree less strongly with the negative statements*. This is most pronounced in the last statement which was posed to users of both tools: "I would need to learn a lot before using 3DIR". As discussed below, it appears that a major concern for the new functionality is the added complexity it entails.

5. DISCUSSION

The results from the 3DIR+Topology evaluation are encouraging but suggest that the added complexity might be difficult for users to grasp. The stronger agreement with statements of the complexity, cumbersomeness and un-learnability may also be a symptom of the speed with which the demonstration was conducted. The software demonstration lasted about twenty minutes, followed by about ten minutes of questions and answers, after which the users were asked to complete the questionnaire. It is also possible that framing the new functionality within the theoretical concept of *topology* added unnecessary complexity. In the demonstration session, the users used terms such as "widening the search criteria" or "finding related items" when discussing the new functionality.

A possibility that was explored was that the lukewarm assessment of 3DIR+Topology was due to the relative inexperience of the cohort of test subjects. Perhaps more experienced professionals would see the value of the functionality more clearly. This was investigated but the results showed that the support for the new functionality was roughly constant for all levels of experience.

It must be acknowledged that the slightly lower scores of 3DIR+Topology indicate that some rethinking is required about the usefulness of this functionality. During the workshop following the demonstration, test participants verbally agreed that the functionality was useful, but the SUS (System Usability Scale) questionnaire scores do not *strongly* support this. This functionality might be a result of "function creep", whereby the gradual widening use of a technology causes it to be unwieldy in its complexity or causes it eventually to shift away from the use for which it was originally intended. Even if this functionality is indeed useful, an improved interface design is needed to make the functionality more intuitive and facilitate the formation of more helpful mental models of the notion of topology. From discussion with test participants, the list of topological relationships exploited (touching, intersecting and hosting) needs to be expanded, and the interface design needs to convey those more clearly.

6. CONCLUSIONS

The 3DIR prototype creates an index of all text data attached to a Building Information Model. The user is able to search for information by selecting specific 3D objects, specifying a spherical region of the model and/or entering search keywords. Search results are displayed by highlighting 3D objects in the 3D model, isolating them or indicating them using a colored balloon shape. The 3DIR+Topology system exploits model topology. At the indexing stage, a separate list of other objects hosting, touching or intersecting each element in question is saved as a list of "Neighbors". When searching a selected set of objects, selected objects containing the search keyword in any of their parameters are shown first in the results. The list of neighbors of each of the retrieved objects is then recursively searched until the maximum number of Hops specified by the user. In a comparative evaluation of 3DIR and 3DIR+Topology, users of the latter agree less strongly with positive statements and disagree less strongly with negative statements. This indicates that, although still useful, more careful interface design is needed to mitigate the added complexity of this functionality. The underlying hypothesis of the 3DIR project remains compelling, that a tighter coupling between the 3D model and textual information is helpful for information retrieval. Future research can attempt to evaluate search results from 3DIR and 3DIR+Topology in the more formal information retrieval sense, using formal measurements of recall and precision.

ACKNOWLEDGMENTS

Our colleague Dr Ann O'Brien is an original member of the 3DIR team and contributed to the original 3DIR work but unfortunately passed away before this paper was written. The 3DIR project was supported by a Brian Mercer Feasibility Award from the Royal Society, with further support from the Enterprise Office at Loughborough University and funding from University's Higher Education Innovation Fund. Autodesk provided support through membership of the Autodesk Developer Network. 3DIR is available for free from http://www.3dir.org/.

REFERENCES

Austin, S., Baldwin, A., Li, B., & Waskett, P. (2000). Analytical design planning technique (ADePT): a dependency structure matrix tool to schedule the building design process. *Construction Management & Economics*, 18(2), 173-182.

Borrmann, A., & Rank, E. (2009a). Topological analysis of 3D building models using a spatial query language. *Advanced Engineering Informatics*, 23(4), 370-385.

Borrmann, A., & Rank, E. (2009b). Specification and implementation of directional operators in a 3D spatial query language for building information models. *Advanced Engineering Informatics*, 23(1), 32-44.

Brilakis, I. K., & Soibelman, L. (2008). Shape-based retrieval of construction site photographs. *Journal of Computing in Civil Engineering*, 22(1), 14-20.

Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability evaluation in industry*, 189(194), 4-7.

Caldas, C. H., Soibelman, L., & Han, J. (2002). Automated classification of construction project documents. *Journal of Computing in Civil Engineering*, 16(4), 234-243.

Demian, P., & Fruchter, R. (2005). Measuring relevance in support of design reuse from archives of building product models. *Journal of Computing in Civil Engineering*, 19(2), 119-136.

Eastman, C., Teicholz, P., Sacks, R., and Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors* (2nd ed.). John Wiley & Sons.

Gemignani, M. C. (1972). *Elementary Topology*. Courier Corporation.

Koo, B., & Fischer, M. (2000). Feasibility study of 4D CAD in commercial construction. *Journal of construction engineering and management*, 126(4), 251-260.

Kunz, J. C., Christiansen, T. R., Cohen, G. P., Jin, Y., & Levitt, R. E. (1998). The virtual design team. *Communications of the ACM*, 41(11), 84-91.

Lansdale, M., & Edmonds, E. (1992). Using memory for events in the design of personal filing systems. *International Journal of Man-Machine Studies*, 36(1), 97-126.

Leslie, H. G. (1996). Strategy for information in the AEC industry. *INCIT 96 Proceedings: Bridging the Gap*.

Lin, K. Y., & Soibelman, L. (2009). Incorporating domain knowledge and information retrieval techniques to develop an architectural/engineering/construction online product search engine. *Journal of Computing in Civil Engineering*, 23(4), 201-210.

Lin, C. J. (2013). Smart Spatial Ontology: Bridging Semantic Ontology to Spatial Topology. *Computer-Aided Design and Applications*, 10(3), 489-497.

Paul, N. (2009). Basic topological notions and their relation to BIM. *Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies*, 451-472.

Pirolli, P., & Card, S. (1999). Information foraging. *Psychological review*, 106(4), 643.

Rezgui, Y. (2006). Ontology-centered knowledge management using information retrieval techniques. *Journal*

of Computing in Civil Engineering, 20(4), 261-270.
Robertson, G., Czerwinski, M., Larson, K., Robbins, D. C., Thiel, D., & Van Dantzich, M. (1998). Data mountain: using spatial memory for document management. In *Proceedings of the 11th annual ACM symposium on User interface software and technology* (pp. 153-162). ACM.
Ugwu, O. O. (2005). A service-oriented framework for sustainability appraisal and knowledge management. *International Journal of IT-Construction ITCon* (Electronic Journal), 10, 245-263.
Veeramani, D., & Russell, J. (2000). Preparing the AEC industry for the knowledge economy. *In Berkeley-Stanford Construction Engineering and Management Workshop: . Defining a Research Agenda for AEC Process/Product Development in 2000 and Beyond*.