Navigating Complex Models in Collaborative Work for Integrated (and Sustainable) Design

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Abstract. The paper discusses geometric-content-based search and classification techniques proposed in order to support collaborative, multi-disciplinary work on building design projects which utilize three-dimensional digital models (e.g. BIM, CAD, CAE, etc.) The rationale for employing such techniques – as an alternative to conventional assigned-attribute-based ones – is presented, based on observed difficulties experienced by users of digital models prepared by parties other than themselves. Also introduced are proposed methods drawing on the field of visual analytics for displaying the results of search and classification operations by augmenting the conventional system of views and tabular information in order to enable users to obtain greater insight into the contents of complex models. Included is a description of preliminary tests undertaken to assess the validity of some of these proposals, and results showing that model users are able to apply the proposed methods for retrieval and organization of information in models, thus overcoming some language-based and other common obstacles typically encountered with exchanged models in collaborative design processes.

1. Introduction

Increasingly intensive uses of computational techniques such as parametric-associative modeling, algorithmic design, performance simulations and generative design in architecture, engineering and construction are leading to production of increasingly large and complex 3D building models which in turn require increasingly powerful techniques in order to be manipulated and interpreted effectively. Further complexities are of course due also to the multi-disciplinary nature of building projects, in which there can be significant variation and even conflict among the aims of architects, engineers and builders, as well as owners, occupants and other stakeholders in the process. Effective use of model information depends to a large extent on sense-making, which can in some ways be helped but also hindered by schemes for organizing the information contained. Common techniques such as layering, labeling (aka "tagging") and assignment of various other attributes to model objects have significant limitations – especially those arising from general problems of language, ontology and standardization, as well as but distinct from issues of interoperability. These limitations arise both with respect to locating the desired items in a 3D building model and also with respect to displaying the objects in informative ways which effectively assist design, collaboration and decision-making. Sustainable design in particular is an area generally requiring a high level of inter-disciplinary collaboration to achieve highly integrated designs which make multiple use of the elements and systems incorporated (though integrated design may also be pursued without explicit aims of sustainability.)

This paper describes ongoing research concerning alternatives to the currently common techniques for locating and displaying information in 3D building models in support of sense-making to promote collaborative and integrated design. These alternatives comprise on the one hand interactive geometric-content-based methods for search and classification of model objects – as an alternative or complement to common assigned-attribute-based methods – and on the other hand visual analytic techniques for processing and displaying model data – in contrast to existing, relatively static tabular and "physical" views – which can help to increase the informativeness of the geometric data within the model, as well as that of the non-geometric data attached to geometric objects (e.g. as in the cases of BIM and various types of CAE performance simulations.) Following this Introduction the context of the problem as observed in AEC practice is examined in more detail in Section 2, while Section 3 deals with the proposed methods for alleviating some of the problems identified – as described also briefly above – and presents research questions. Section 4 describes the implementation of the proposed methods as software tools and the tests undertaken with architects and engineers in practice and academia to evaluate the proposed methods, including results. Finally conclusions are drawn regarding the tested methods' positive present performance and some of their shortcomings, as well as indicating directions for future research concerning the methods' refinement and extension in order to help 3D building models become more effective components of the design process than they are at present, both with respect to these models' present levels of complexity and especially with respect to their anticipated increasing complexity in future. While the proposed methods do not offer a comprehensive 'solution' to the problems encountered in collaborative work in architecture, engineering and construction – such as that required for sustainable building – they do constitute the foundations of an approach which could eventually go a long way toward some of those problems' resolution.

2. Context – the research problem

The gradual replacement of 2D representations by 3D digital models is to some extent enabling collaborative processes of design, analysis, communication and decision-making which were not feasible previously. Yet it has been widely observed both in practice and academia that the use of these 3D digital models also poses some significant difficulties, particularly regarding the exchange of models in the kinds of multi-party, multi-disciplinary design processes which characterize AEC practice. (But these are rather less prevalent in academia, which in this field tends to remain less oriented toward collaborative, interdisciplinary work, except as an object of research). Practical experience as well as observation of and interviews with users of 3D digital building models in commercial practice have shown that a number of distinct but partly overlapping and otherwise interrelated factors are hindering the effective exchange, interpretation and manipulation of such models, including among others interoperability, differing methods of representation, and incompatibilities of language, as described below.

Interoperability concerns largely the internal representation of model objects within the software as well as what attributes are recorded – e.g. what subset or version of a naming convention such as IFCs is implemented – and how these data are exported/imported. Much effort has already been and continues to be devoted to addressing this problem [1, 2, 3, 4, 5], which is largely technical in nature, rather than arising primarily from matters of cognition and differences between users or cultures (although differences in naming conventions such as those mentioned can have cultural aspects, as discussed below.) As a result, data transferred from one program to another is lost or else misinterpreted by the receiving program. One expedient way of addressing this is to eliminate the technical hurdles by having modelers all using the same software – though in many cases this is not practical or desirable – but even if so, the two other factors mentioned remain problematic.

The need for alternative representations arises especially in inter-disciplinary model exchanges, where not only does the receiving party need only some (usually small) part of the information provided in the "basis" model to create a new model, but frequently the objects present in both models are nevertheless represented differently – not only at the level of internal data, but also differing in visible form and characteristics. Thus, although some of the information needed to carry out a particular task may be found in one or more existing models of the project, it is often not sufficient to just find and reuse the relevant model objects. Instead it is often necessary to convert them via mappings to other forms which practically speaking – at least from the point of view of digital data – are other objects (called here "derivative objects" because they are derivable from existing objects, in contrast with other objects which must be created "from scratch"). This is not to say that a single "object" could not have multiple representations associated with it, thus shifting the object's identity from geometry to some other, more abstract area, but this is not the case in current modeling software which while it does usually allow for different visualization modes to be applied to a set of objects changes only their appearance, but not their geometry. The creation of alternative representations is possible to automate in some cases, but not in others. [6, 7] This point touches on the issues of "centralized" versus "federated" models and of generating task- or discipline-specific "views", but centralized models are rarely practicable [8], and the automated generation of "views" presenting relevant subsets of the total data collection – represented alternatively as needed – is in any case still subject to problems if it relies on assigned attributes such as object names for determining the relevance of objects and for deciding how to operate upon them.

Language also poses obstacles to smooth flow of data (as well as information) between disciplines and between software platforms. Frequently it is observable that indeed, current assigned-attribute-based methods of organizing and retrieving information are inadequate, because one person's or firm's or industry sector's way of naming things may not correspond with that of others with whom it must exchange data.

"Different disciplines have their own unique languages and customs that allow for ease of communication and rapid exchange within the community, but misunderstandings and general lack of exchange between groups. The more a discipline becomes 'specialised', the greater is its ability to make progress … on the problem at hand, but [the] less its ability to communicate to outsiders" [9].

But the usual remedy proposed for mis-communication is standardization, by which those who propose it assume that language incompatibilities will be eliminated. [10, 11] However, this approach overlooks two important factors: first, that standardization of naming (i.e. naming conventions, such as STEP, IFC, etc.) are difficult or impossible to implement widely enough to substantially address the problem, and second, that forcing standardization of naming would have a number of detrimental side-effects which might entirely negate the gains realized. Asserting the difficulty of standardization is supported by the increasing recognition among proponents of the approach – even those actively participating in the creation and promulgation of standards – that they are simply not being adopted despite years of effort [3]. This is not proof, of course, that further efforts would not eventually succeed, but even if they did, the second point remains salient: forced universal adoption of naming conventions would eliminate one of the necessary tools for creative, inventive thinking and design. Whereas such conventions can be appropriate and even necessary to convergent thinking where the set of all relevant problems and acceptable solutions is known, and it is simply a matter of retrieving or deducing the right solution after correctly identifying and analyzing the problem, only little of actual building design is really of this nature. [12, 13] Instead, new ways of conceiving and tackling the design brief are constantly embarked upon, and new ways of solving the eventually identified problems are constantly emerging – even aside from considerations of formal invention, but just looking at new materials and products. Naming conventions simply cannot keep up with such proliferation, nor can they adequately anticipate all the needs which might drive the choice of names used to describe its outcomes and by-products. Collaborative work requires some common understanding, but this is not to be found by plastering over the participants' differing points of view with imposed names chosen from a centrally determined list (unless the list is so long as to be unwieldy, and even then it must allow for metaphorical usages.) Rather, an open system is needed which supports divergent thinking – or "expandable rationality" [14] – and accommodates the varying needs of different users and situations.

Attribute-based organization and retrieval of model objects (and data in general) also poses a number of other potential problems, including the possibilities of non-attribution or of mis-attribution, as well as the magnitude of effort required to assign attributes to large numbers of data items, which makes it impractical unless automated – in which case the problems of language above arise again, since an automated attribution system will only be sensitive to the needs of one or of some situations, but will assign names or other attributes which are non-meaningful, insufficiently meaningful, or even overly meaningful in many other situations. Thus, we must also look elsewhere than assigned attributes as a way of searching for relevant information (and in some cases also as a way of further manipulating it to produce alternative representations) when interpreting geometric models received in a collaborative design process.

For purposes of analysis in this research project – to better understand how we may intervene when addressing the problems noted above – the activities involved in the observed exchange and manipulation by users of 3D building models have been categorized into three broad types, or phases, which take place more or less sequentially but usually also iteratively at various scales (see Figure 1) :

1. Identification – the stage of examining a received 'basis' model and determining which of the objects it contains are relevant to the subsequent task;
2. Construction – the stage of creating a model using the relevant objects found in the previous stage, and when needed, converting those objects to others which constitute alternative representations of them;

3. Expansion – the stage of adding to the new model further objects not found among those in the received model, nor derivable from them, as well as adding other, non-geometric data to complete the new model.

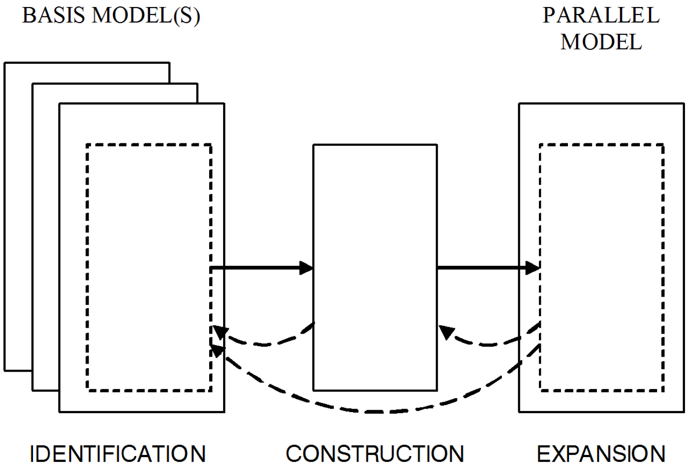

Fig. 1. Diagram of the activity cycles in model interpretation and creation.

As noted already, these stages of model interpretation and creation tend to follow one another in the order shown, but often iterative loops may return focus from one activity to the previous one(s), for example when a period of Construction reveals a need for further information which might be sought by continuing the Identification activity. The critical stage from the point of view of collaborative work is Identification, where the language and other accustomed information-organizing schema of the modeler confront the schema present in the received model, which may not be (and, as observation shows, usually are not) entirely congruent. This essentially describes a problem of "sense-making" [15, 16].

It has also been observed in practice that users of 3D digital building models are able to interpret received models without recourse to annotations, object names, layer names, colors and so on – although having these available can be helpful when reliable. Instead, model users can make sense of the model's contents "simply" by looking at the depicted objects and their arrangements, and drawing conclusions about the nature and role of each object that enable them to proceed with whatever task they wish to carry out. (This may include organizing the model with their own system of names, layers, etc., as well as producing alternative representations of some model objects and adding further objects and supplemental information.) Of course the actions of vision and interpretation are far from simple, and the relative importance to such cogntitive tasks of the objects' own characteristics in proportion to their interrelations is also open to question, but the fact that model users can reliably find and categorize objects – i.e. view models and interpret their contents sufficiently well to perform activities of identification, construction and expansion – without explanatory text, tags, or the like suggests a pivotal role of geometry in sensemaking which we can try to make use of for improving model exchange operations. More specific proposals for doing this are described in the following sections, but here we note again the key distinction between our use of the terms "geometric content" – with which we denote the model's geometric objects (including subelements such as edges, faces, etc.) – and "assigned attributes" – such as object and layer names, colors, etc. which are often language - or convention-dependent and which can be assigned to the model's objects by users or by automation. Whereas it has been observed that the assigned attributes can be insufficiently meaningful (or even misleading) to the recipient of a model, the geometric properties may let us access objects more nearly in the way that we do via visual cognition, tapping into concepts such as size, orientation and shape. This could help us in making sense of received models' contents in collaborative design processes where the language-based and other notational conventions of interacting parties might not be shared closely enough to promote mutual intelligibility.

3. Proposals – hypotheses

Taking into account the obstacles to effective collaborative use of 3D digital models noted above, we can propose some specific ways of addressing the situation by developing user-guided (rather than automated) methods which have the capacity to be more responsive to the particular needs of particular situations, and by implementing them as tools which users can interactively apply while examining and manipulating models. Furthermore, the methods should be geometric-content-based to circumvent difficulties of assigned-attribute-based methods described above. The need for interactivity arises on two fronts : first, for fitting tools to specific situations, i.e. to the different needs of different firms, tasks, people, and so on without attempting the impossible anticipation of all these situations; second, displaying information in various ways so as to enable users to gain insights, following the principles outlined in the field of visual analytics [17]. Geometric description is to supplant or complement the role usually played by language in organizing and retrieving model objects, seeking to avoid the various problems identified earlier by letting us access the model's objects via what we see of them, rather than via what others have said about them.

To focus the investigation more narrowly and put the issues into terms which admit of experimental study, we can formulate the following relevant research questions :

- Can interactive geometric-content-based methods for search and classification effectively aid users of 3D digital models in organizing and retrieving model data ?
- What techniques of visual display can be applied to make more meaningful the results of search and classification operations beyond the currently common ones of tabular and "physical" views ?

To clarify the above, we note that :

1. geometric-content-based methods are ones which rely on inherent ("immutable") characteristics of the geometric objects in the model, in contrast with the currently common assigned-attribute-based methods (i.e. those employing layers, colors, "tags", etc.);
2. "physical" views here denote those commonly employed display modes in which the model's geometric objects are made visible as geometric objects from one or more projections (e.g. plan, front, side, perspective, axonometric, etc.), in contrast with more abstracted modes where the objects are replaced by, for example, graphic symbols and/or alphanumeric data – the latter as in the case of tabulations; and
3. "tabular" views are those in which the model data are displayed in alphanumeric form, typically with one row for each object in a particular collection and columns conveying the assigned attributes and possibly also geometric information or other annotations associated with each object. (This view type can also enable some kinds of geometric querying and sorting.)

Other investigators have also hit upon geometric-content-based methods of search and classification as a way of alleviating some of the obstacles to effective 3D model use, but their approaches differ from that proposed here. In the first place, most object recognition research is aimed at general-purpose identification; thus, vehicles, plants, human and animal figures, furniture, mechanical components and so on are all to be evaluated and classified by the same algorithm [18, 19, 20]. Contrastingly, the approach taken here is specific to the building domain. In the second place, these other approaches are highly automated, with minimal interactivity, [21, 22] whereas the present approach preserves the users' intelligence as an active component of the search-and-classification process [17, 23] Thirdly, topology is usually taken to be of prime importance [20, 24, 25], which is appropriate when the scale and posing of the objects is not known, but ignores the informative capacity of geometric properties such as dimension and orientation as are found in the objects comprising building models. This touches upon a fourth point – not quite as significant as the first three but still noteworthy – which is that many object recognition approaches are concerned with identifying models of single (often complex) objects within large repositories of models, whereas in building design we encounter within one single model many objects, individually often quite simple in form, but assembled in potentially very complex arrangements. [7, 26]

Experimental study of the issues above proceeds then, in this case, with formulation of a hypothesis that user-guided geometric-content-based methods of search and classification – expressed more compactly as "user-guided feature recognition" – can be implemented as software tools which will allow 3D digital model users to effectively find and retrieve geometric objects in such models without having to rely on assigned attributes. Specifics of the proposed methods' implementation and testing are presented in the section which follows.

4. Implementation – Testing and results

4.1. Apparatus

Implementation of the methods described above as a software tool proceeded in stages, the first ones of which were concerned with exploring the workings of various types of queries and means of displaying results via particular scenarios focusing on one or two technical issues at a time, via "mini-tools" created for evaluation by self-testing. By this method, a number of basic questions were addressed such as :

- which geometric characteristics or combinations thereof have significant object distinguishing capabilities within the domain of common building components ?
- what logical structures can be used to evaluate model objects with respect to given search criteria, and how does the choice affect performance in such respects as speed and relevance of retrieval ?
- how are issues of numerical accuracy to be dealt with in evaluating conformance of a geometric value or quality with a search criterion ?
- what do different kinds of graphical and alphanumeric display techniques offer in terms of meaningful display of such geometric query results ?

Among the issues mentioned above two are seen as being particularly influential : object evaluation and results display. Following identification of geometric characteristics which are able to distinguish among object types (the specific characteristics themselves are of less importance, since object types can be distinguished in a variety of ways, as discussed also later) the issue arises of how a query using these characteristics – assuming that more than one at a time is to be used – can be structured, and also how each object's conformance to the query is evaluated. One can view the characteristics forming the query as a group of filters through which the data comprising each object is passed, so we are concerned here on the one hand with filter arrangement – e.g. parallel vs. series – and on the other hand with "scoring" – that is, how the object data's relation to or satisfaction of each filter is measured. These factors influence both the speed of evaluation (which becomes a significant usability issue for large models) and the ability to distinguish relevant objects, as well as eventually impacting the user's access to these evaluations' results via the method(s) of display discussed subsequently. For example, in a case where a query is composed of three characteristics, we can evaluate these sequentially in various orders – potentially speeding the process by terminating it in the event of nonconformance to an earlier criterion and thus saving the time needed to evaluate the following one(s). Or we can evaluate them "in parallel", thus checking against each criterion every time. In either case, there exists also the potential to "score" the evaluation with a simple "yes" (the object meets all of the criteria) or "no" (the object meets none or only some of them) or else to report also partially conforming results which may give the user more insight into the model's contents and assist in formulating further queries. (See Figure 2). In addition, each criterion can itself be scored on a binary basis ("yes"/"no") or in many cases also with a more nuanced system of discrete or continuous values. In the case of evaluation in series, the order of evaluation also can influence scoring, if partial matches are to be reported.

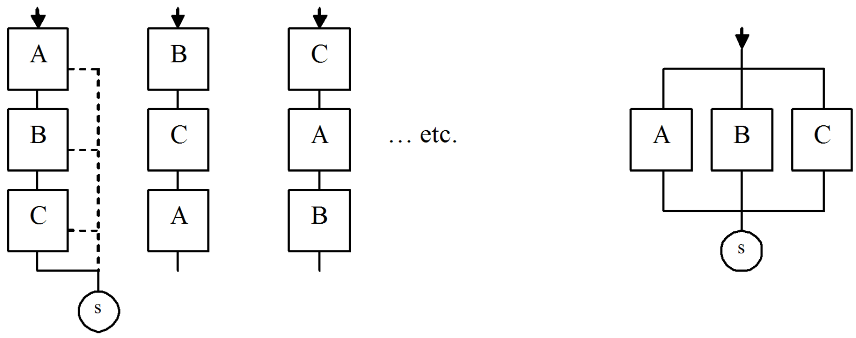

Fig. 2. Evaluation and scoring schemes for object data filters : series (left) and parallel (right).

The display logic used to report results is also dependent upon and can reflect these different scoring approaches – yes/no results can often be indicated simply by giving a single color to conforming objects, for example, while partial matches can be shown with color gradation proportional to relevance and/or with other colors used to indicate ranges of relevance. (See Figure 3.) The use of different colors to denote "bins" of objects corresponding to various ranges of a criterion's value can be effective in quickly distinguishing multiple categories of objects with a single query, instead of requiring a separate query for each category.

The implemented geometric-content-based search/classification methods are user-guided and interactive in keeping with the needs noted in the previous section. User-guidance is manifested in the choice of query type employed, which affects both the type and number of query parameters exposed for editing, and also affects the logical structure by which the model's contents will be compared to the query parameters. Since the query types are non-exclusive in their logic, different query types can be used for similar searches, according to the user's needs. For example, column-like objects could be searched for by using the "column" query type (exposing only orientation/inclination as an editable parameter) or by using the "beam" query (which again exposes inclination, but uses a different internal logic in evaluating objects) or by using the "panel" query (which exposes more parameters and also uses a different logic in comparing objects to the query terms.)

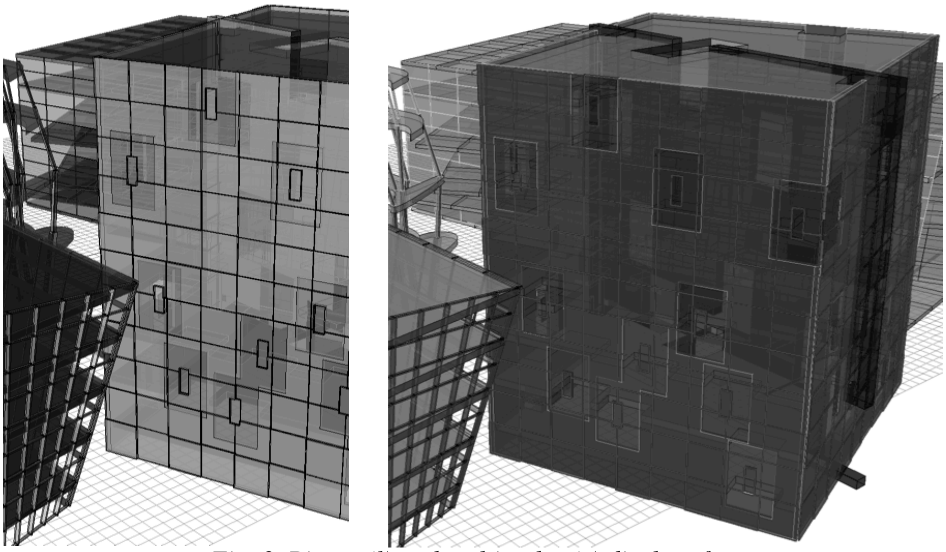

Fig. 3. Binary (l) and multi-color (r) displays for reporting search/classification results.

All of these query types are capable of identifying column-like objects, and all would identify mostly the same objects as being column-like, though usually not exactly the same set of objects due to differences in logic even with comparable exposed parameter settings. Interactivity of results display in this implementation is achieved by the choice of query type and also by the editing of parameters, which in some query types allows the user to focus on different subsets of a larger object set meeting the query terms nearly, if not exactly. We note that although the approach and implementation described here emphasize 3D objects, they are also adaptable to 2D- and 1D- objects in 3D space.

4.2. Experiment

For the experiment, volunteers of both similar and differing backgrounds were recruited from a number of commercial firms and academic institutions in various countries, as follows :

- Architects (57%) and Engineers (43%).
- Practitioners (65%) Academics (21%) or Both (14%).
- German (24%) Dutch (13%) Brazilian (10%) Turkish, Italian, English (7% ea.) Albanian, Australian, Austrian, Bulgarian, Chinese, Indian, Polish, Portuguese (3% ea.).

The participants were presented with a laptop computer running a commonly used general-purpose 3D modeling software package and displaying a building model comprising approximately 2400 model objects including commonly encountered element types – such as floors, walls, windows, columns, etc. – as well as some more ambiguous ones. All of these objects were initially uncategorized, that is, they had no assigned attributes indicating type, either by color, name or otherwise. After a brief explanation of the experiment (and a short introduction to a few relevant operations of the modeling software for those who had little or no prior experience using it) each participant was asked to spend 20 minutes sorting the model objects into categories by visually examining and assigning them to layers. Some layers had been predefined (e.g. "columns", "slabs/decks", "walls" with sublayers "bearing" and "partition", "façade" with sublayers "panels" and "frames"), but latitude was left to add new layers, rename or delete existing layers or otherwise modify the categorization system to fit their own perception of an appropriate scheme, if desired. The selection and assignment of objects to categories was carried out in this part of the experiment using whatever techniques the users were familiar with (or had been introduced to) including individual selection, selection by windows, and selection by layer or color. Following this first 20-minute categorization activity, the participants were debriefed for a few minutes, focusing on description of how they had chosen to organize the model's contents and how this related to their usual working practices.

In the second part of the experiment the participants were again presented the same model of uncategorized objects as before, with the same initial set of empty layers available for use or modification, and then given a brief introduction to the use of the tool implementing the "user-guided feature recognition" methods described above. Again they were asked to spend 20 minutes categorizing the objects in the model, but this time by using the tool rather than the previous set of selection techniques. At the end of this activity they were again debriefed, and the experiment concluded.

4.3. Results

Most of the participants were able to complete both parts of the experiment within the alloted time, although some of those without prior experience using the given software or 3D digital modeling in general did not categorize all objects. In the first part roughly half of the participants used the pre-defined set of layers with little or no modification, while the others created substanitially modified layer schemes, ignoring or deleting the predefined layers. Whereas these highly modified schemes also differed substantially from each other in various respects but not others, the less modified schemes tended to be quite similar to each other, even in the choice of new layers created and also in the choice of which pre-defined layers to use, ignore or delete.

In the second part of the experiment, the number of uncategorized objects was generally the same or higher for each participant than in the first part, although 90% of subjects did categorize all objects. All participants were able to use the geometry-based tool to some extent, and all were able to produce object categories which were consistent with the categorizations they produced in the first part. However, many participants found that the tool provided in the second part enabled them to make finer distinctions among objects than they made with their usual selection techniques, and this was reflected in some cases by an increase in the number of layers created and used in the second part.

In addition to providing positive evidence regarding the feasibility and effectiveness of the proposed interactive geometric-content-based and visual-analytic techniques for search, classification and exploration of 3D digital building models, the test results also supported an underlying assumption and motivation of the proposed approach (drawn from experience, interviews and observation of model use in practice), namely, that different people do tend to name the same objects differently, even when these people practice the same specialty or discipline, indeed, even when they work together in the same organization.

5. Conclusions

The proposed techniques for geometric-content-based search and classification of 3D digital model contents can promote collaborative work by helping model users to overcome differences in language (including national differences as well as naming conventions within one language) and other conventions of assigned-attribute-based organization of model contents. Testing has indicated that 3D digital model users with various backgrounds and levels of skill and experience in modeling are able to apply such techniques through software tools such as the ones described in the Implementation section herein. Thus, in situations where people need to work with models created by others, as is commonly the case in multi-party, multi-disciplinary design processes, they are able to make more effective use of those models by complementing or circumventing the conventional assigned-attribute-based techniques which are currently prevalent. This in turn can contribute to the rapid evaluation and feedback necessary to successful collaborative work [23].

Such content-based methods relying on geometry can also be helpful to people working with their own models, in order to reorganize information within them as well as to perform analyses and other inquiries into their models' contents. Having found information of relevance, they may of course choose to organize it using assigned attributes (e.g. by naming categories of objects), but the important point is that the next user of the model need not rely upon the previous user's naming to find information of relevance. Whether exploring their own models or those made by others, users of such interactively operated tools can benefit from their action as "learning devices" [14] helping the acquisition of insights and formation of concepts.

To the extent that the model data analysis and query techniques implemented result in visualizations and that the analyses, queries and visualizations can be interactively modified by the users to yield insights regarding the models' contents, the methods and tools described belong to the area of visual analytics, whose growing repertoire of analysis, interaction and visualization techniques offer promising extensions to the implementation described herein [17].

Some shortcomings of the proposed techniques observed or inferred from the work so far include :

1. limitations regarding the users' ability to modify the queries, arising on the one hand from a lack of sufficient knowledge about the appropriate level of complexity for queries – in terms of the number of parameters exposed for editing by the user – and on the other hand the issue of custom-built queries vs. modification of predefined queries, where the former comprises not only exposing some parameters while "hard-coding" others but also giving users the opportunity to assemble themselves a set of parameters and criteria by which to form a search query (or class definition); and

2. the tools' and methods' limited capacity to express queries based on relationships between objects, rather than the qualities of objects themselves, such as those relationships emphasized in topologically based approaches. Whereas some such queries can be carried out within the framework of the proposed system, for example by identifying a set of relevant objects (by

whatever means chosen) and then creating a geometry-based query to find all objects meeting certain criteria such as intersection-with, containment-within, distance-from in particular directions, etc. this can be a rather roundabout approach (compared with an explicitly topology-based one) and not all queries can be effectively answered by these means. Thus, explicitly topologically oriented methods would provide a good complement to the geometry-based ones.

Another possibly underlying reservation is that while easier exchange of model contents via the reuse of data enabled by techniques such as the proposed ones makes for more efficient collaborations (particularly in terms of reducing the time required to create new models), the overall effectiveness of the collaborative design process may be better served in some cases by preserving the necessity of re-creating model information and by the potential for verification and/or re-interpretation which this action entails. However, determination of this via testing would be very difficult, so it may be better to leave the choice of streamlined versus conventional process open.

Further testing would examine a number of remaining questions and issues, including investigation of the query-formation mechanisms described above and also carrying out experiments in which the task is more explicity collaborative in nature, such as by having models passed back and forth between users performing different tasks, whether within the same discipline or in differing disciplines. Another area of interest for further investigation concerns the role of visualizations in the effectiveness of these search and classification techniques' use, to understand in more detail which ways of displaying results are more effective, and how users' ability to interactively influence the display methods (e.g. by changing range and focus as well as colors and other graphical qualities of the display) may further affect their ability to interpret results.

On the whole, however, it is clear that geometry based user-guided feature recognition methods such as those described and tested here can take advantage of much of the content of building models which is significant in transdisciplinary terms and thus can contribute to the sensemaking necessary for enabling collaborative work. Reducing reliance on standardized naming can help preserve the relevance of computer based techniques to design activity as well as to production processes by supporting divergent as well as convergent thinking and enabling invention beyond the combinatorial potentials of a "kit of parts". Although the methods described and tested are not aimed expressly at sustainable design, clearly this is one area of concern in the building industry and also the building sciences where integrated, collaborative and inventive approaches are essential for success, and it is hoped that techniques based on the proposals made in this research will find an appropriate role to play in supporting such collaborations.

6. Acknowledgements

Thanks are due to all of the individuals who participated in the interviews and/or experiments, as well as the firms or institutions which made their participation possible, including : the Architectural Association, Arup Associates, Atelier Ten, Bollinger+Grohmann, CASE, Delft University of Technology, Design to Production, osd, Planomotor, Transsolar, University College of London, Werner Sobek Ingenieure, and Zaha Hadid Associates.

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