

PERSPECTORS

Inferring spatial relations from building product models

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Abstract. Building product models are beginning to find their way into AEC practice. They are proving useful for coordinating large multidisciplinary design and construction teams. In an evolving design and construction planning process, building components are added, modified, or deleted from the product model, causing important spatial relationships to emerge. In addition, new criteria can emerge throughout this design and planning process, causing particular spatial configurations of building components to become of interest. Current practice for building product models relies heavily on explicit representation or on visual inspection to determine conditions of interest. As models become larger, and more complex, visual inspection and/or explicit representation become prohibitively difficult. Formalized automated reasoning mechanisms are needed to complement formalized representation strategies. This paper presents two cases from the Walt Disney Concert Hall, a project using a detailed 3-D building product model, where current practice failed to provide the team with required information. Practitioners need a user-customizable tool that can analyze the building product model and consistently and rapidly identify instances of these spatial conditions based on the current state of the model. We formalize reasoning mechanisms called *perspectors* that analyze a building product model and add objects, attributes, or relationships, based on the analysis. We use these *perspectors* to infer implicit spatial relationships between building components, making these relationships explicit.

1.0 INTRODUCTION: THE NEED FOR AUTOMATED REASONING MECHANISMS FOR BUILDING PRODUCT MODELS

The immediate purpose of this research is to enable queries for emergent spatial configurations of building components in building product models. When collaborating to improve a design and its construction plan, design and construction professionals routinely modify, add, or delete design information. Consequently, new important spatial configurations between building components emerge. Today, practitioners must identify these emergent spatial configurations in a slow, manual, and error-prone process that hinders the flexible reuse of product models across disciplines and through the life of a project. If product models supported queries about the implicit spatial configuration of building components, professionals could rapidly construct consistent and up-to-date project representations for their work, and product models created by one discipline could be more readily used for the work of other disciplines.

The issue of emergent spatial relationships between building components is symptomatic of a more fundamental issue in building product modeling: Balancing the need for discipline specific representations of a project with the need to integrate these representations with the work of other disciplines. Current practice and research attempts to address these issues in one of two ways: Some attempt the explicit representation of all domain’s concerns in one integrated model, while others propose the use of multiple, domain specific models. This paper illustrates that both approaches do not adequately support a design and construction process where design data and criteria are incrementally added, modified, and deleted. Actions of one discipline often have emergent effects on the concerns of other disciplines that remain undetected. In addition, as the design evolves, new criteria often emerge that the existing data representation is unable to support.

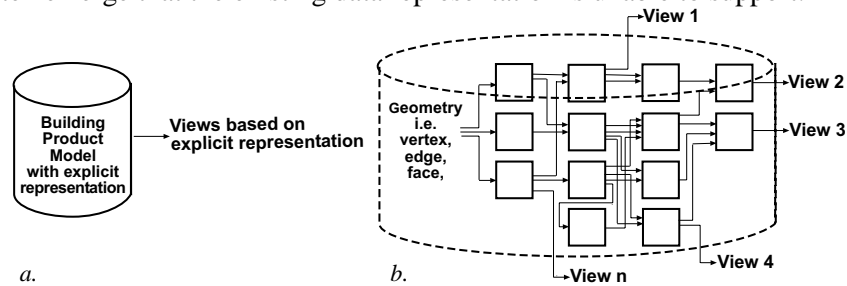


Figure 1: A simplified depiction of the role of ‘Perspectors’: mechanisms that take in data and add objects, attributes, and relations (o,a,r), based on a particular perspective.
 a. shows a product model containing more explicit data, with no perspectors, capable of producing only predefined views; b. shows geometry augmented with perspectors, capable of producing representations of implicit conditions in the product model .

This paper therefore argues that a formalized approach that augments representational approaches with automated reasoning about these representations is the best approach to adequately handle emergent conditions and criteria. We propose mechanisms, called ‘Perspectors’*¹, that modularize the process of constructing domain specific representations of a building product model. Given an existing representation of a building product model, each perspector adds, modifies, or deletes objects, attributes or relationships to this representation, shown schematically in Figure 1. This representation modification can involve explicit representation. For example the ‘Beam Perspector’ could annotate product model geometry as a ‘beam’ through user selection of which geometry constitutes a beam. Or the view modification can involve automated reasoning, algorithmically inferring from the geometry which shapes satisfy the beam criteria. The net result of this ‘Beam Perspector’ is a classification of which geometry constitutes a beam. Users can connect Perspectors into larger structures to create more complex views, for example finding beams in the product model that have a particular spatial relationship to slabs. Perspectors should simplify the act of representation, while increasing the flexibility and reusability of building product models by allowing users to construct representations of the project, that incorporate modular reasoning, suitable to a particular user’s criteria.

In this paper, we use perspectors to infer complex spatial relationships between building components. We specify the required representation, consisting of a set of relevant geometric features of building components, and a set of spatial relations between these features. Macro-features aggregate spatial relations between features to form a representation of the condition between building components that is of interest. For reasoning, we use a series of perspectors that formalize the transformation of a product model without certain explicit spatial relationships, into a product model with spatial relationships.

With this framework, a user will be able to specify the particular spatial relationships (i.e. above) between particular features (i.e. top face) that are of interest, aggregate these selected relationships between features into a macro-feature (i.e. slabs that have a particular spatial configuration with their supporting beam), and direct the computer to search the database for all sets of components that implicitly satisfy the macro-feature requirements. The system can then explicitly create these spatial relationships in the

The term Perspector combines the words :

‘Prospector’ – referring to the mechanisms that search through a database, and
‘Perspective’ – implying a certain semantic bias to that search.

product model, and present the instances of the specified criteria to the user with different types of views, such as a tabular list, or a 2d or 3D representation, suited to the task at hand. Figure 2 gives a diagrammatic preview of our system in the context of a test case, presented in section 2, involving a particular set of spatial relationships of interest between a slab and a beam. The system is explained in section 4

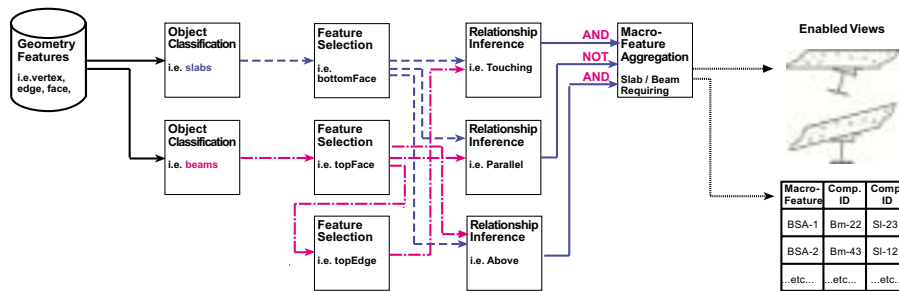


Figure 2: A series of *Perspectors* (denoted by a box) work together to transform a building product model with implicit spatial relations into a building product model with explicit spatial relations. Output of one *perspector* serves as the input to the next *perspector*.

Design and construction planning involves the incorporation and negotiation of multiple domains criteria. Potential solutions satisfying the criteria of one domain often have emergent effects on the criteria of other domains. This research claims that formalized, automated reasoning is needed to manage the propagation of effects between domains. We investigate *perspectors* in general, and automated spatial reasoning in particular, as a step towards a formalized, general approach to reasoning about these product models. *Perspectors* enable the automated construction of domain specific representations from a shared geometric product model. If successful, *perspectors* would:

- Simplify modeling by allowing practitioners to model fewer explicit semantic concepts.
- Increase the usefulness of the models as a collaborative tool by allowing disciplines not doing the modeling to construct useful queries.
- Modularize the construction of queries, allowing incremental construction, modification and reuse of both representation and reasoning components, on an evolving product model.
- Enable ‘live views’ – views are automatically updated when data changes
- Enhance the power of the product model from a static project documentation tool, into an active project-reasoning tool.

1.1 OUTLINE OF PAPER

We first present the case for automated spatial reasoning in the context of the Walt Disney Concert Hall (WDCH), designed by Frank O. Gehry and Associates (FOG/A), and constructed by M. A. Mortenson Company (M.A.M.) , in Los Angeles, California. The WDCH's expected completion is 2003. The WDCH project uses 'state of the art' 3-D building product models as an integral coordination tool for design and construction. We present two examples from the WDCH where spatial reasoning mechanisms would have helped the practitioners perform their design and planning tasks.

We then present the current state of research and practice relevant to our goal of inferring spatial relationships of building components from a building product model. We discuss, in light of the WDCH example, why existing a priori and a posteriori classification approaches alone will not satisfy our requirements for quickly and accurately detecting spatial relationships of interest. We describe the fundamental points of departure, in the domains of product modeling and spatial reasoning that provide the necessary formalisms to augment existing product modeling approaches to achieve our requirements.

Next, we present our system of perspectors that construct spatial relationships between building components. Our representation consists of a set of geometric features of building components, and a set of spatial relationships between these features. These spatial relationships are aggregated to form a macro-feature describing the spatial configuration between building components. For reasoning, we propose a series of perspectors that help to transform a product model without certain explicit spatial relationships, into a product model with spatial relationships.

The final section of this paper discusses future work in this research, and speculates on potential academic and practical contributions and implications of automated spatial reasoning and perspectors for building product models. There has been significant development towards a formalized approach to representing product models for the AEC industry. We investigate perspectors in general, and automated spatial reasoning in particular, as a step towards a formalized, general approach to reasoning about these product models.

2.0 TEST CASE: THE WALT DISNEY CONCERT HALL

The WDCH is to be the new 2290-seat home for the Los Angeles Philharmonic Orchestra. The Architects, FOG/A, are recognized internationally for their daring designs, their innovative and advanced use of 3-D modeling to represent their designs, and the integral role these models play in the construction process. To our knowledge, the WDCH represents some of the industry's best practices in terms of the collaboration of multiple disciplines using large amounts of 3-D electronic data. This project, therefore, serves as an ideal test case to explore how designers and construction planners from different disciplines interact with these models to support their work. These best practices introduce new challenges and opportunities in the way professionals interact with the building product models.

Consistent with The Center for Integrated Facility Engineering (CIFE) research practice, the first author spent several months on the job site working along side the construction planners and architects. During this period, while working on the issues of the day and constructing a series of 4-D models, we monitored the current practice looking for real world problems with fundamental theoretical shortcomings that academic research could help resolve.

The 3-D building product model for WDCH is constructed using CATIA V4, a powerful 3-D modeling program common in the automotive and aviation industries. The scope of this paper does not cover the specific process for constructing and sharing this model, for this we refer the reader to Haymaker and Fischer (2001).

In this section we present two situations from the WDCH project where the current 3-D building product models failed to adequately support practitioners in their design and construction-planning tasks. In the first situation, a slab and beam meet at unique angles, requiring the addition of miscellaneous steel components. In this situation, the designer required a local view of each location where this condition occurred. In the second situation, ceiling panel supports meet the ceiling panels in a number of ways. In this case, the designer requires a more global view, to understand how these conditions are distributed throughout the ceiling system.

In these situations, if a user had a tool that enabled them to formally define conditions of interest conceptually, allowing the tool to find the instances of these conditions rapidly and consistently, the user could have found appropriate solutions faster and more inexpensively.

2.1 A SLAB AND BEAM CONNECTION REQUIRING ATTENTION

Emergent spatial conditions of interest can occur when two components are positioned proximately in space. The WDCH has numerous conditions where the steel beams and concrete slabs meet at unusual angles. These occur mainly where a floor slab meets a slanted wall, or where a slab slopes, such as at a roof, or theater seating. In these conditions, as shown in Figure 3, a steel angle is needed to close the gap to assure the slab is properly supported. The architect and structural engineer do not locate these angles, they are left for the contractor to locate, size, detail and install.

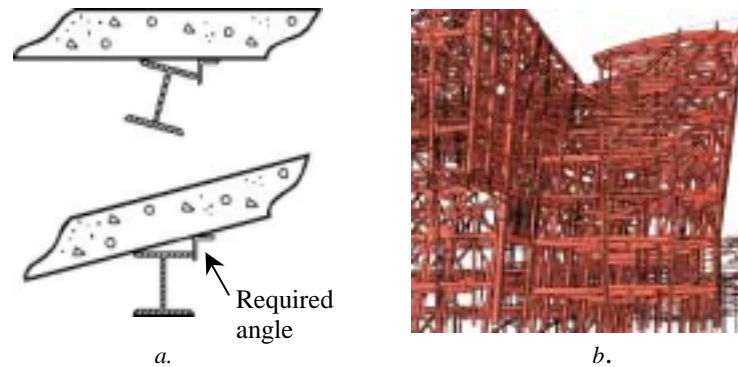


Figure 3: a. A slab slopes in relation to the beam, requiring an angle for support.
b. A portion of the complex steel model for the WDCH.

Finding these situations required M.A.M. to use a highly skilled and expensive CATIA engineer to manually navigate through the complex 3-D model (figure 3b), and visually locate and annotate each individual condition. This process is unsatisfactory because:

- The task consumed three full weeks of the engineer's time and was difficult and un-gratifying for the engineer and expensive for M.A.M.
- There is great likelihood of missed conditions that could result in costly delays in the field.
- New conditions could emerge due to design changes after the inspection took place, leaving these conditions undetected.
- New criteria could emerge, for example certain slab types may no longer require the added support due to a metal decking detail, requiring the search to be repeated, taking into account this new criteria.

Practitioners need a user-customizable tool that can analyze the building product model and consistently and rapidly identify instances of these spatial conditions based on the current state of the model.

2.1 EDGE OR CANTILEVER SUPPORT CONDITIONS OF CEILING PANELS

The concert hall ceiling is an architectural and acoustical structure hanging from the WDCH roof trusses. The ceiling integrates lighting, mechanical, A/V systems, and a concrete acoustical fill into a curvilinear wooden ceiling finish, shown in Figure 4a and b, with roof trusses and ductwork also shown. The design is daring and complicated.

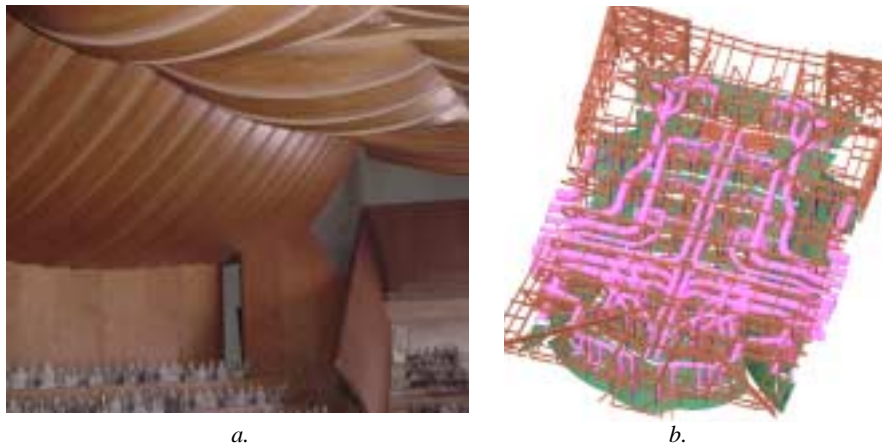


Figure 4: a. The WDCH ceiling from below (image from a FOG/A physical model) and b. from above including roof framing and ductwork (image from the 3-D product model)

FOG/A is proactive in integrating the knowledge of contractors and sub-contractors into the design process to build these complex designs. They develop the building product model to the point where it communicates architectural intent, along with some schemes for how it might be built, then forward these to the contractors for their input. The ultimate ceiling framing strategy, whether it becomes a pre-cast concrete system, a light gage steel framing solution, a structural steel framing solution, or some combination of these, was left to the contractor to determine. The design team predetermined the ceiling support drop locations to allow mechanical and other design work to proceed, yet these drop locations could change during design development to suit architectural, mechanical, structural or acoustical demands (see Figure 5 b). The scope of this paper is not to tell the entire story of the ceiling analysis, but to present a situation during this process where the spatial reasoning mechanisms we propose would have been useful.

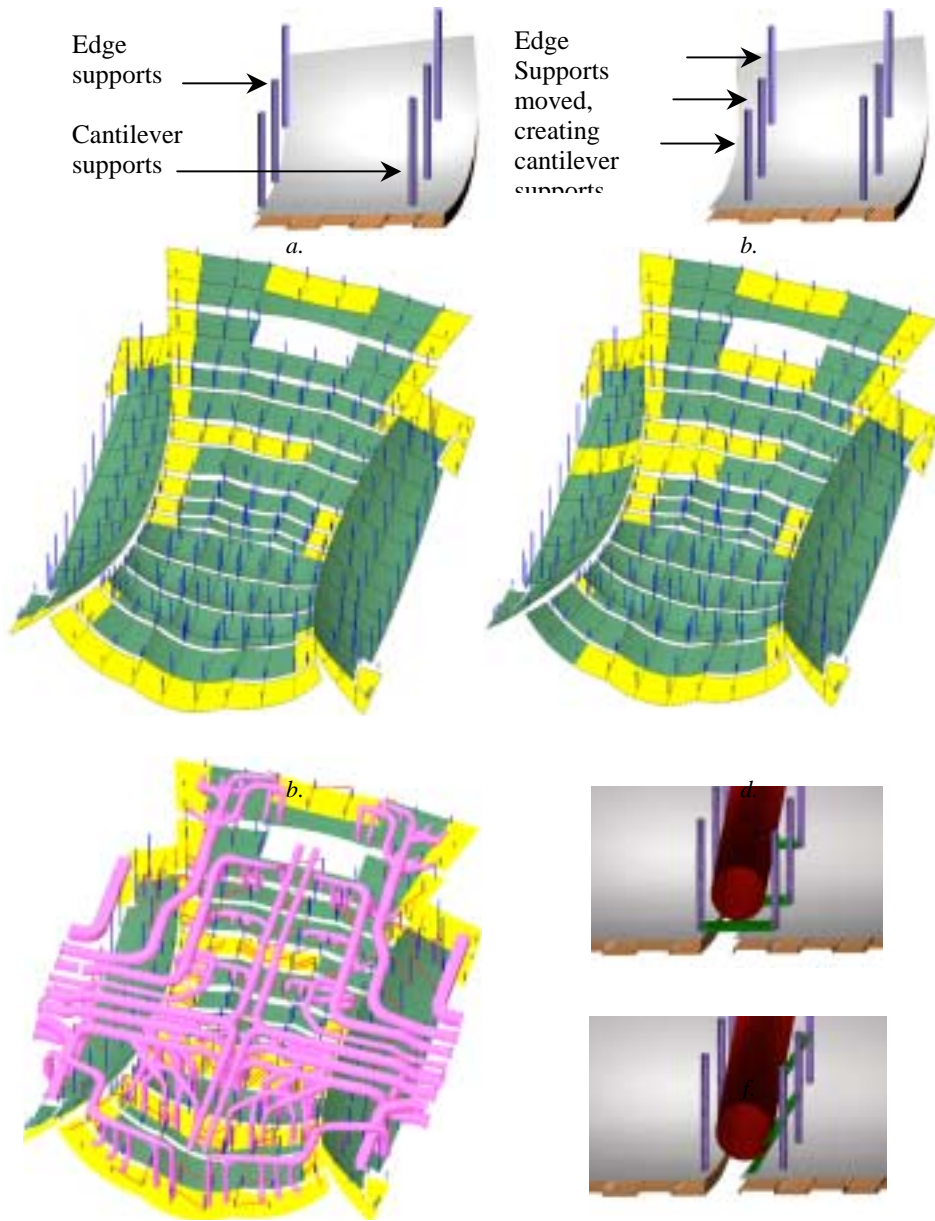


Figure 5. Moving supports (a and b) can have emergent and global effects. A practitioner wants to keep track of which panels contain cantilevered supports (c, and, after some supports are moved, d). They also want to understand these cantilever conditions in the context of the ducts (f) so they can choose the best way to support the cantilever (f and g).

The ceiling system was panelized to aid constructability, and these ceiling panels were to be fabricated elsewhere, and trucked to the site for installation. Some of the panels had cantilevered support conditions, while others had edge support conditions (figure 5 a and b). While considering the structural solution for the panels, the design team wanted to know how many of these cantilevered conditions occur, how severe the cantilevers are, what the distribution pattern of this condition is throughout the entire ceiling (figure 5 c and d), and how this distribution of cantilever conditions interface's with other building components, such as ducts, in the design (figure 5 e), to help decide how best to resolve the cantilever condition (figure 5 f ,g).

While it would be possible to visually inspect the model, determine where the condition occurs, and annotate the building product model accordingly to construct a view such as figure 5c, this approach contains difficulties:

- Panel supports could be moved, creating the need for repeated inspection, or missed conditions.
- The criterion for what a cantilever is differs depending on the structural solution chosen. The light gage framing method can span less distance than other solutions, before a cantilevered detail is required.
- The visual inspection and annotation process is laborious, error prone, and restricts a more fluid 'what-if' design process that would allow the designer to explore many alternatives.

2.3 LIMITATIONS OF CURRENT PRACTICE

What is needed for the two cases presented in this section is a methodology, previewed in figure 2, for defining the spatial condition of interest conceptually, and allowing the computer to do the difficult, repetitive, and error prone task of finding all of the instances matching this spatial condition in the building product model. In this way, if something in the design changes, the computer can update the views automatically. Similarly, if the concept changes, for example, if the criterion for cantilever changes slightly, only the concept needs to be altered, and the views can be updated automatically. In the next section we explain why existing strategies of a priori and a posteriori classification of data, while a valid starting point, do not adequately address our requirements for a user-customizable tool that can analyze the building product model and consistently and rapidly identify instances of these spatial conditions in the model at any point in time. We identify relevant research that serves as a point of departure towards meeting these requirements

3.0 POINT OF DEPARTURE AND LIMITATIONS OF CURRENT RESEARCH

This research seeks to augment existing product modeling approaches with spatial reasoning mechanisms, implemented using our concept of perspectors, to create explicit spatial relationships. Figure 6 presents a specification for spatial reasoning perspectors as an IDEF diagram. We detail the system in Section 4, but provide the diagram and brief explanation here to set up our discussion of points of departure. This section describes points of departure in the representation of product models from the AEC and mechanical engineering domains in Section 3.1, reasoning about these product models in Section 3.2, and spatial reasoning from the domain of cognitive psychology in Section 3.3.

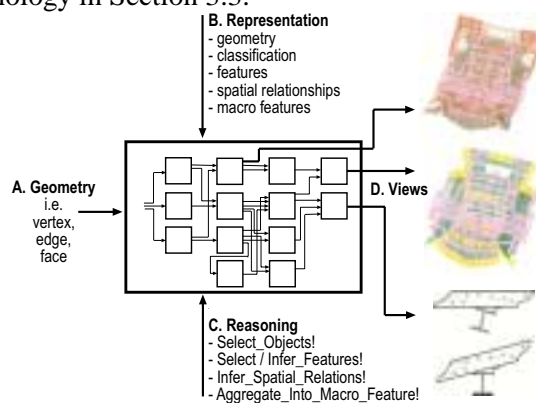


Figure 6: An IDEF diagram describing spatial reasoning perspectors

Figure 6 can be understood as follows:

- A. At the root of a series of perspectors is the 3D project geometry. We explore a geometry consisting of vertices, edges, and faces here, although perspectors could be coded to expect other geometrical representations.
- B. Perspectors expect a particular ontology, beginning with a geometrical representation that the spatial reasoning mechanisms are prepared to analyze. Perspectors then incrementally construct semantics, using the ontology of classification, features, spatial relationships and macro-features.
- C. Perspectors implement reasoning algorithms to analyze the building product model to create explicit macro-features that are used to create views (D). Through analysis of the test cases at the WDCH, we have identified the listed reasoning algorithms (which are each implemented as individual perspectors) as significant steps in inferring the macro-features.
- D. The output of these perspectors is an augmented instance of a building product model containing the macro-feature of interest. This augmented representation can be used to generate views.

3.1 PRODUCT MODELS

A number of researchers have worked in the domain of product modeling, defining the relevant objects, attributes and relationships in a building product model. Some of these product-modeling approaches investigate a central shared model incorporating all project views (IFC, 2001) while others propose multiple, domain specific models with integrity relationships between the models (Turk 2001, Rosenman & Gero, 1996). Some (Bjork, 1987, IFC, 2001) explore a *semantically* explicit approach providing specific objects (i.e., 'beam'), attributes (i.e., 'W16 X 50'), and relationships (i.e., 'supports'). Others approach the problem *syntactically*, providing more abstract structures such as objects, attributes and relationships that can be extended to create a particular ontology (Phan 1993, Stouffs, 1997). Some of these approaches can be used *a Priori*, or at design time (IFC, 2001, Gielingh, 1988). Others are intended to be used *a Posteriori*, or during design inspection. (Clayton, 1999, Hakim & Garrett, 1997). We will now discuss the benefits and drawbacks (Zamanian & Pittman, 1999) of each of these approaches, followed by a discussion of our system of perspectors in this context, as a system that maximizes the benefit of each of these approaches, mitigating the drawbacks, and incorporating reasoning as part of the representational approach.

3.1.1 Integrated model vs. multiple domain specific models

A major problem on large, multidisciplinary projects is the coordination and communication between the different disciplines. One approach to addressing these issues is through construction of an integrated product model that contains all of the objects, attributes, and relationships relevant to all of the disciplines involved. As building product models become larger and more complex, and as greater numbers of disciplines seek to collaborate using these models, strategies relying on explicit representation of all disciplines concerns in a shared model break down. The multidisciplinary concerns are too numerous and difficult to represent explicitly by the disciplines doing the modeling, maintaining integrity of relationships in the product model during design collaboration is too complex, and the models are too large to ask each individual discipline to visually inspect the models continuously throughout the process for emergent effects.

Other research explores the use of multiple, domain specific models, similar to the traditional paper-based approach, allowing representations suited to individual domains concerns (for example, the structural engineer may represent a beam as a line annotated as a W16 X 50, and type of connection to other columns and beams explicitly represented. The steel detailer may

represent this beam in full detail, with holes, bolts, and connection plates represented explicitly. The architect may want to represent how this beam intersects a non load bearing, fire-rated wall, and is therefore interested in the profile, etc.) Integration of these views is either performed in coordination meetings (similar to the traditional approach) or through complex integration rules (such as the beam in the structural engineer's view is the same as the beam in the architect's view) allowing changes in one domain's view to be propagated to the other domains representations. When these integration rules are used, the difficulties described in integrated models, explained above, are again encountered.

This paper advocates an integrated geometric product model, using a mixture of shared and domain specific semantic representations to annotate and transform this geometry to achieve domain specific views. We extend other similar approaches by incorporating modular reasoning mechanisms into the representational structure.

3.1.2 Syntactic vs. semantically explicit. approaches

Existing product modeling approaches contain a wealth of formalisms to represent the syntactics and semantics of real world concepts of interest. Syntactic approaches formalize many of the concepts such as object classification, features, and relationships that we require to represent macro-features between components (see figures 2 and 7). These syntactic approaches provide a framework within which to define semantic concepts, allowing great flexibility in the types of concepts they can describe. However, syntactic approaches do not explicitly formalize specific semantic concepts, making sharing data across projects, and writing general analysis software for the industry difficult. Semantic approaches explicitly define objects (i.e., 'beams'), attributes, (i.e., 'steel grade'), and relationships, (i.e., 'supports'), with which to construct a specific project's product models. These approaches generally enable more semantic data sharing between applications, but the encoded semantics are often too brittle to adequately describe many real world situations.

Figure 7 gives an example of how the Industry Foundation Classes (IFC's) (IAI, 2001), the proposed standard from the Industry Alliance for Interoperability and a semantic approach, can be used to model the slab and beam example from section 2. Figure 7 identifies notions of classification, geometric features, constraints and relationships, coinciding closely with the steps, specified in Figure 2, that we use to construct spatial relationships. The annotation suggests that, for our goal of automatically inferring spatial relationships from these building product models, the IFC's and other

product models contain much of the formalisms required to adequately represent the existence of a relationship between components. However, these representational approaches must be extended. Current product modeling approaches lack a representation of certain features, of the specific spatial relationships between features, and the ability to aggregate these relationships into a descriptive macro-feature.

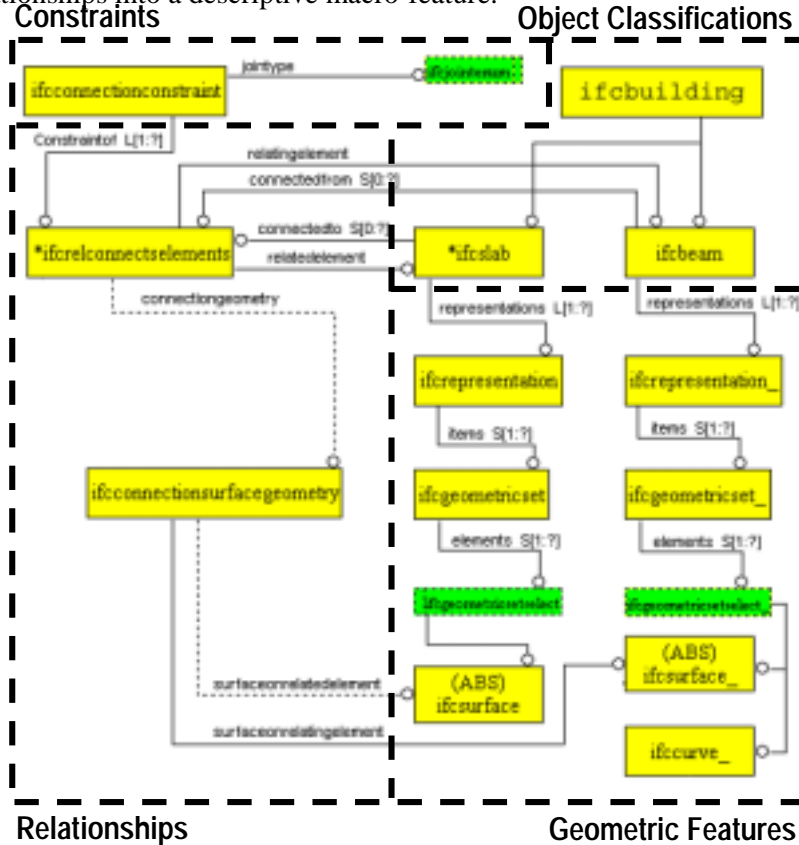


Figure 7: A (simplified) representation of the slab-beam example using the IFC ontology, represented in Express-G. Concepts not explicit in the IFC begin with a capital letter.

The framework of perspectors is essentially a syntactic approach, but can be used to encode semantic concepts. we use the IFC as a point of departure, using their formalism where it is available to describe many semantic concepts such as ‘beam’. The emphasis on the syntactic approach allows for many project specific concepts to be built on top of these shared industry concepts. In addition, by formalizing reasoning as part of this syntactic approach, we simplify the application of user defined semantics to the specific project data.

3.1.3 *A Priori vs. A Posteriori application of schema*

Some research intends for the application of semantic schemas to the design at design time. Some CAD programs (IAI, 2001) allow you to create IFC objects such as beams, slabs, and spaces, etc, explicitly during design. Other approaches acknowledge that disciplines other than the ones doing the modeling will want to construct different semantics onto the data, allowing users to semantically label the design as they inspect it.

Attempts to explicitly represent conditions as they are created (i.e., when components are positioned), which we term 'a priori' because they are classified before the view is required, are difficult because:

- The discipline generating the change often does not understand the implications on other domains, or does not understand that the configuration has significance until later in the design process.
- Such exhaustive data entry interrupts the natural way designers work.
- There is great potential for errors and omissions.
- Concepts often emerge during the design and planning process that cannot be predicted.

Asking each discipline to inspect and classify the data after it has been created (i.e., when the view is required), which we term 'a posteriori', is also not practical because:

- Data is often updated incrementally, requiring the users to repeat the review task incrementally.
- Visually inspecting a database with thousands of components is prohibitively time consuming.
- There is great potential for errors and omissions.

The approach of perspectors allows for both strategies. A software package could construct a beam perspector as it generates the data, or it could allow a user to create this perspector when inspecting the geometry. The system of perspectors extends both of these approaches by offering a third alternative, representing the concept of beam algorithmically, and allowing the computer to infer which geometry satisfies the beam criteria.

3.2 MODEL BASED REASONING

Existing Product modeling approaches also lack the ability to dynamically update to changes in the design, or to address evolving concerns of those using the model. Some approaches (IFC 2001, Eastman, 2001) define constraints between objects that include tests for validity of these constraints. However, these constraints are applied in an a priori fashion as part of the object definition, not allowing for a posteriori automated analysis

of the implicit relations between building components. As the WDCH test case shows, practitioners need a mechanism that defines a spatial configuration between components conceptually at any time, and look for instances in the building product model that satisfy this conceptual spatial relationship of interest.

Existing approaches do not, however, propose a formal way for reasoning about the model. Our goal is to develop and test a theory for perspectors that can be used with any of these product-modeling approaches. We seek a formalized reasoning model to complement representation models, providing the added flexibility to query the model for objects, attributes, or relationships that are not explicitly represented in the model. In this paper we explore perspectors in the context of spatial reasoning.

In the mechanical engineering domain, Rosen and Dixon (1994) recognize the need for the inference of implicit relationships in the product model. He proposed a general process that, through what he calls a process of filtration, annotation, and aggregation, could infer these types of relationships. While these insights for the need and general process are valuable, they did not develop or formalize the notion of annotation (analogous to our requirement for inference of spatial relationships).

Researchers at the Center for Integrated Facility Engineering (CIFE) and elsewhere have worked in the area of model-based reasoning with models incorporating geometry. Most of this research has been done in the context of a single domain, and on domain specific models. Among some of the CIFE projects, Darwiche (1988) and Aalami (1998) perform model-based reasoning to produce a construction schedule; Akinci (2000) analyzes a 4-D model to infer time-space conflicts for workspace; Akbas (2001) analyzes project geometry with productivity constraints to determine daily work zones; Fischer (1993) analyzes product models for constructability concerns; Han (2000) analyzes an IFC based product model for handicapped accessibility; Korman (2001) performs MEP coordination, and Staub-French (2000) works on the automation of cost analysis. Outside of CIFE others have created similar model-based reasoning systems. Among these Dym et al (1988), and Amor (1992) perform automated Architectural code checking. Others work to perform a series of tasks around an integrated product model Aouad (1997), and Laitinen (1998).

Perspectors, as a mechanism that analyzes a building product model and adds, modifies or deletes objects, attributes or relationships based on the contents of the model are an approach towards a generalized framework for model-based reasoning. Perspectors enable the transformation of an

integrated geometric product model into domain specific representations that allow each of the system described above to perform their analysis.

3.3 SPATIAL REASONING

To address the two required extensions to the product-modeling domain, representing the spatial constraints between components, and inferring these constraints from a building product model, we turn to the domain of qualitative spatial reasoning. In this section we briefly identify relevant research in this domain, which help to represent and infer spatial constraints between geometric features. We describe the formalisms of orientation and topological relations, conceptual neighborhoods of these relations, and frames of reference.

Zimmerman and Freksa(1996) identify the qualitative relationships between a path and a point as consisting of the 15 possibilities shown in figure 8. Hernandez extends this idea to create a hierarchical ordering, showing that ‘in front of’, can be further decomposed to ‘front-right’, ‘front’, and ‘front-left’, etc. We need to extend these notions to 3-D, however, the insight that the relationships between two components can be classified into a finite and hierarchically structured representation is valuable. For example, a practitioner may look for any slabs that are above the beam (with orientation of ‘above’ implied by gravity), or he may want to specify that all light switches be placed to the right of the doors (in reference to the exiting direction). We discuss orientation in greater detail below.

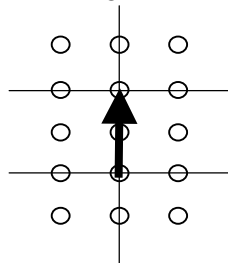


Figure 8: Freksa’s relationships between a path and a point in 2D. We extend these relations to 3-D and apply the hierarchical ordering proposed by Hernandez.

Both Egenhofer (1991) and Hernandez (1994) discuss the notion of topological-orientation pairs to further describe the spatial constraints between objects. In addition to the orientation relations discussed above, one can refer to two objects as ‘disjoint’, ‘touching’, ‘overlapping’, ‘contained-within’, etc. It is therefore possible to further constrain the relationships between two objects, or features of objects, as a pair of orientation and topological constraints. One can therefore say something is

[above, touching]. For example, we may ask for the slabs that are above and touching the beams. These researchers also identified the existence of conceptual neighborhoods, where certain orientation-topological pairs are neighbors of other orientation-topological pairs. It should therefore be possible to identify neighborhoods of relations that are of interest (i.e., [front,touching] \rightarrow [right,disjoint]), rather than just an individual relationship. Figure 10 shows a partial conceptual neighborhood diagram of orientation-topological pairs, as formalized by Hernandez.

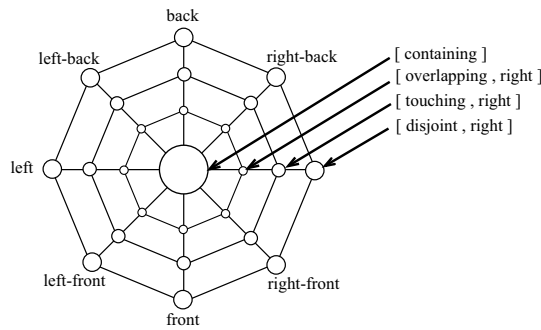


Figure 9: Hernandez' conceptual neighborhood of orientation-topological pairs.

Orientations occur within a frame of reference. If one says 'the light switch is to the right of the door', this occurs within one of three frames of reference:

- Intrinsic: where orientation is given by an inherent property of the object (i.e. right, in reference to the doors exiting direction)
- Extrinsic: where external factors impose orientation on the reference object (i.e., right in reference to the rooms orientation)
- Deictic: where orientation is imposed by the point of view from which the object is seen. (i.e., right from where the observer is standing)

These formalisms from the qualitative spatial reasoning domain provide a framework to represent the individual spatial constraints between geometric features that can then be aggregated to form a descriptive spatial relationship between building components. We now combine these contributions from the product modeling and spatial reasoning domains to specify a system that can achieve our requirements for a fast, error-free, and automated process of detecting spatial relationships of interest in building product models.

4.0 USING PERSPECTORS TO INFER SPATIAL RELATIONSHIPS

Motivated by the requirements for a consistent, rapid, on demand, and up-to-date process for inferring implicit spatial relationships between components in a building product model, two limitations in current product modeling research have been uncovered.

First, there is no formalism to represent spatial relationships, and aggregations of spatial relationships between geometric features of building components to describe spatial configurations of building components. Formalisms from the product-modeling domain appear sufficient for representing geometric features (as shown in Figure 7, although these need to be extended to include semantic modifiers such as ‘top face’), and formalisms from the spatial reasoning domain appear to be an excellent starting point for representing the relationships between the features. A representation structure to aggregate the relationships into a descriptive macro-feature is still needed. We currently use a simple aggregation. For example:

```
(slab.bottomFace Above beam.topFace, AND  
slab.bottomFace Touching beam.topEdge AND NOT  
slab.bottomFace Parallel beam.topFace)
```

The second limitation in current product modeling research is the lack of a formal way to automatically detect instances of these spatial relationships in the building product model. We formalize the notion of perspector, as a mechanism that analyzes a product model to produce new objects, attributes, and relationships for that product model as a necessary building block for constructing complex reasoning structures. Figure 2 shows a series of perspectors, which, as an aggregate describe the skewed spatial relationship between the slab and the beam. Figure 10 re-represents this process, showing how an instance of slab and beam are processed through the perspectors to check for, and represent the concept

Analysis of a number of WDCH test cases suggests that this process: *Classification* → *Feature Selection* → *Relationship Inference* → *Macro-Feature Aggregation* can be used to describe many different spatial relations between components.

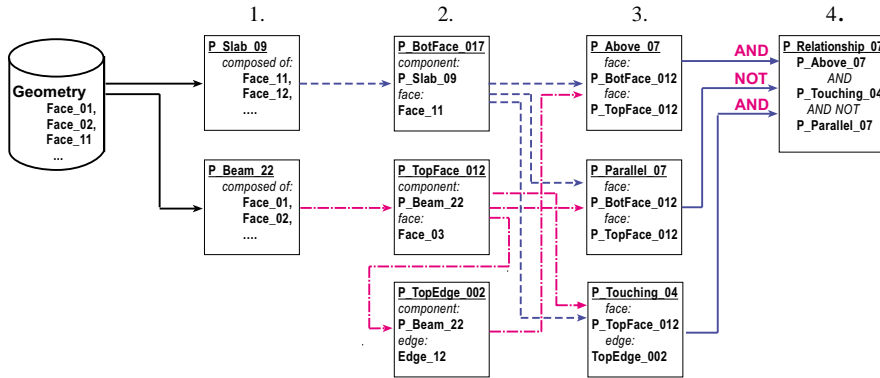


Figure 10: Perspectors analyzing a geometric model for the slab-beam macro-feature

Figure 10 can be understood as follows:

1. The ‘classification’ perspectors, search the data for ‘slabs’ and ‘beams’. These could be more specific classifications (i.e., ‘cast-in-place’ concrete slabs) or more general classifications (i.e., ‘structural members’).
2. The ‘Feature Selection’ perspector accesses the component’s available features. In our system we explore faces, edges, and points, but additional semantics can be applied to the feature selection. For example, the user may be interested in the ‘top face’, or the ‘web’. These can be either explicitly represented in the database, or a perspector could be written to infer which is the relevant feature.
3. A feature on one component is compared to a feature on another component through a relationship perspector. For example, the user states that the ‘top edge of the ‘beam’ should be ‘touching’ the ‘bottom face’ of the ‘slab’. These relations could be represented explicitly in the data, or more likely, they are implicit, and these individual perspectors would infer the relationship between these features.
4. If the relationship conditions are met, they are aggregated into the macro-feature describing the configuration of interest.

5.0 CONCLUSIONS IMPLICATIONS AND FUTURE WORK

The test cases from the Walt Disney Concert Hall that showed that explicit representation in a product model breaks down as the models become large, and the multi-disciplinary concerns become complex. Specifically, the test cases showed how emergent spatial relationships between building components could not have been represented a priori, and visually identifying conditions a posteriori is equally problematic.

We present the notion of a perspector as a mechanism that analyzes a building product model, and returns a building product model with

additional objects attributes and relationships. This reasoning capability would allow practitioners to construct simpler product models, knowing that certain types of objects, attributes, and relations can be easily inferred. We explore a product model consisting of solely geometric features (face, edge, vertex). Semantics are applied to features through layering of perspectors.

Not all of these transformations need to be reasoning based. Perspectors can employ both reasoning and representation for the same concept. For example, 'Object Classification', can simply be a query to the database requesting all geometry that has been classified as a beam. However, object classification could also embody analysis that infers from a series of geometrical features (faces, edges, vertices, etc.) which objects are beams. The output of the 'beam perspector' can then be used for higher-level queries. Such a modular approach would allow multiple representation vs. reasoning strategies on the same database, and allow incremental additions to the reasoning capability on the building product model. We explore the use of perspectors to infer spatial configurations between components.

Working with perspectors should simplify modeling by allowing practitioners to model fewer explicit semantic concepts, while increasing the usefulness of building product models as a collaborative tool by allowing disciplines not doing the modeling to construct useful queries. Perspectors could help transform the product model from a static project documentation tool, into an active project-reasoning tool, providing consistent, rapid, and up-to-date views of user-defined concepts.

We are currently implementing a prototype using the WDCH test case. Using the spatial reasoning mechanisms, users will be able to construct spatial relationship queries on the complex geometry to find conditions of interest. We will test the performance for locating these conditions using this system against actual performance at the WDCH. We will also seek to implement other types of reasoning and product model transformations using the formalism of perspectors.

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