EXAMPLES OF PRODUCT MODEL TRANSFORMATIONS IN CONSTRUCTION

Product model transformations

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Abstract

This paper discusses the results of a case study of product model transformations and geometric reasoning techniques for a challenging project. The complex geometry in the Experience Music Project offers unique challenges in construction processes. Manual transformation of the design-centric product model prepared by the architect into a production model for construction is time-consuming. We discuss ways to transform a design view of a product model into a construction view emphasizing the value of product models supporting multiple views. Geometric reasoning aids in the planning, scheduling, coordination of the project, and modeling of temporary structures. We are developing methods to support these product model transformations using the geometric model.

Keywords: Geometric reasoning, integration, multiple views, product modeling

1 Introduction

There has been a great amount of research in product modeling and symbolic reasoning for construction in the last decade. The results are gradually put into action. With the advent in product modeling techniques, uses and value of 3D CAD systems are increasing. Besides, advances in CAD/CAE systems make it possible to design more complicated structures that once seemed impossible. However, there is still a gap in the interface between the design and construction views of the product model. Most of the research efforts have focused on the design-centric view of the project, rather than on how it evolves during the project life cycle.

We have defined product model transformation mechanisms to transform design-centric product models into production-centric models (Fischer et al. 1998). Product model transformations provide the tools that make the product model a living electronic model of the project. Our ongoing research elaborates the requirements for product model transformations by defining the necessary representations for multiple views and geometric reasoning techniques. Once a product model with transformations is defined for a project, it supports the exchange of design information, enables 3D and 4D visualizations at various levels of detail, automates quantity takeoff and duration calculations, and so on.

This paper starts by describing the case study project. Next, by elaborating on the product model for the case study, we illustrate the transformations necessary for construction projects and the requirements for the representation of the product model. Finally, we explain the geometric reasoning mechanisms necessary to perform these transformations.

2 Motivation for product model transformations

An increasing number of design-build projects, as well as challenging architectural design and construction methods, require complex product model representations and transformations. One recent example is the Experience Music Project (EMP) in Seattle.

Construction of this structure is challenging in several aspects. The exterior is formed by sculpture-like surfaces with variable curvature in all three dimensions. The skin on the Experience Music Project consists of reinforcement, shotcrete, waterproofing, insulation and exterior steel plates and is supported by curved steel ribs. These ribs are in turn braced with secondary steel and support reinforcing bars. Figure 1 shows the components of the 3D CAD model. The complexity of the skin surface requires the contractor to apply several methods of construction at different locations. The project site is located in a bounded area near the center of the city. There is only one entrance to the site, which creates a significant accessibility problem. The site is congested, and laydown areas are quite limited.

The 3D CAD model is the basis for the construction documents at the site. The designer developed some unconventional 3D surface models of the buildings. This geometric information is sent to the construction site. However, the representation is not sufficient for construction. The general contractor has the primary responsibility in managing the data flow and distributing the information to the subcontractors. The interpretation of the CAD model is time-consuming. Participants do not have an automated method for creating their own product model view and updating it in case of a change, which makes it difficult to achieve a consistent data flow.

A design-centric product model alone cannot support the concurrent design and analysis necessary to develop an efficient and safe approach for construction. The designer develops the skin-surface model of one of the building elements shown in Figure 1. The CAD model of the skin includes the interior and exterior surfaces of the shotcrete, material properties and dimensions. Since no reasoning tools exist, the use of this model on the construction site is limited, namely to observe the shape visually and to check for interference with the temporary structures.

The left side of Figure 2 shows a cross-section of one of the building elements of the EMP. It shows how the construction operation varies depending on the curvature of the skin and the distance from the edge of the building. In nearly vertical areas near the edge of the building (1) workers will install the reinforcement and shotcrete, i.e. spray-on concrete, from scaffolding. In steep areas in proximity to the edge of the building (2) workers will use platforms cantilevered from the scaffolding. In almost flat areas (3) workers will work with tie-off to the structure. In steep areas away from the edge of the building (4) workers will need additional scaffolding and tie-off to perform the work. Each of these construction methods has different resource and space requirements and has different production rates.

To plan the use of resources and space over time and to predict the duration of skin installation, the planners need to calculate the quantities of reinforcement and shotcrete from the 3D CAD model. Therefore, they need to break up the 3D CAD model into zones related to the four construction methods. There is a need for a toolset that allows users to break up a 3D CAD model in new ways according to certain criteria (in this case the curvature, the height and the distance from the edge). This toolset needs to reason about the geometry. The right side of Figure 2 shows a decomposition for the given problem.

Meanwhile, the structural engineer has a different view of the project, and is interested in the rings of shotcrete in his analysis for structural stability during construction. The shotcrete surface, therefore, has different geometrical representation in these views.

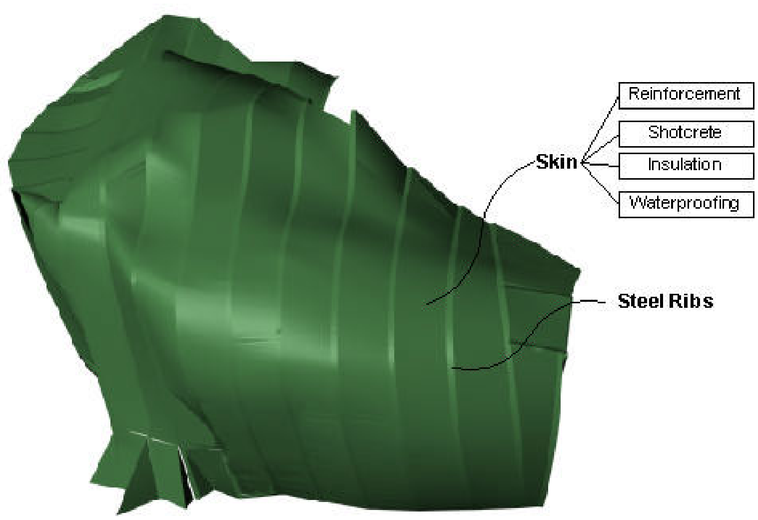

Fig. 1: Components of 3D CAD model for EMP element 7

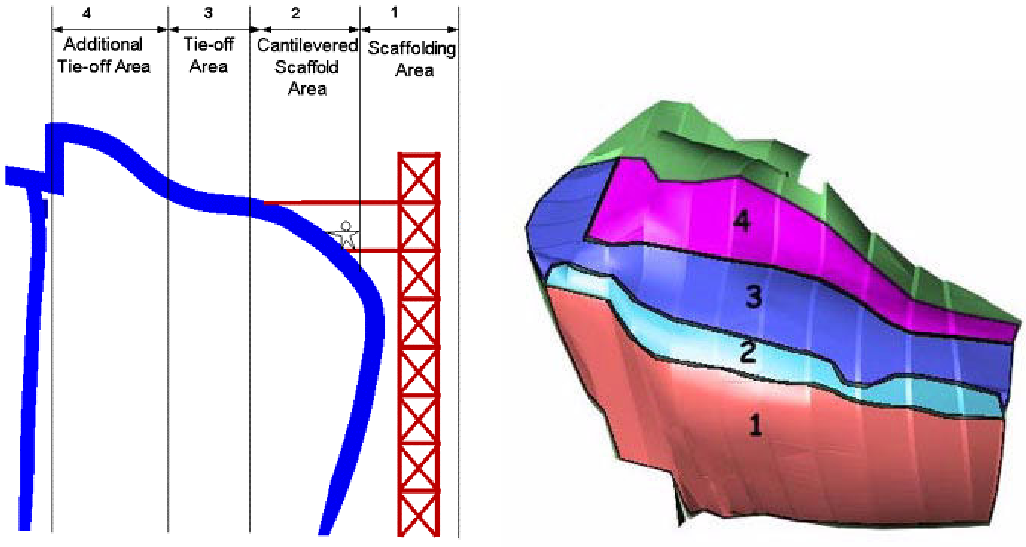

Fig. 2: Construction methods for Shotcrete in EMP element 7

Participants have interdependent objectives. The objective for the detailed structural design is to ensure structural stability when only part of the skin has been completed and the structure is loaded asymmetrically with wet shotcrete. The objective for construction is to allow the subcontractors to employ construction methods that lead to productive construction operations and a safe and efficient use of resources. A particular method, sequence, and speed of construction, in turn, might affect the structural reliability of the half-finished skin.

It is difficult to solve these problems without relying on the detailed 3D CAD model at hand. The need to generate alternative plans is remarkably high in this complex structure. Furthermore, it is hard for the project participants to achieve a common understanding of the construction methods. To satisfy these needs, we are developing the framework for product model transformations. In a fast-track project like EMP, there is a continuous need for product model transformations. Many researchers have emphasized the importance of transformations (or maps) between views (Jeng and Eastman 1998, Van Leeuwen and Wagter 1998).

3 Product model transformations

We have defined the typical mechanisms for transformations from design to construction, and illustrate them with examples from the EMP. The sample product model hierarchy in Figure 3 shows these transformation mechanisms.

3.1 Elaboration

This mechanism decomposes a single object into m objects (m>1). Elaboration is one of the most common transformation types from design to construction. In the EMP, the design-centric model represented the shotcrete surface as one object, i.e.,

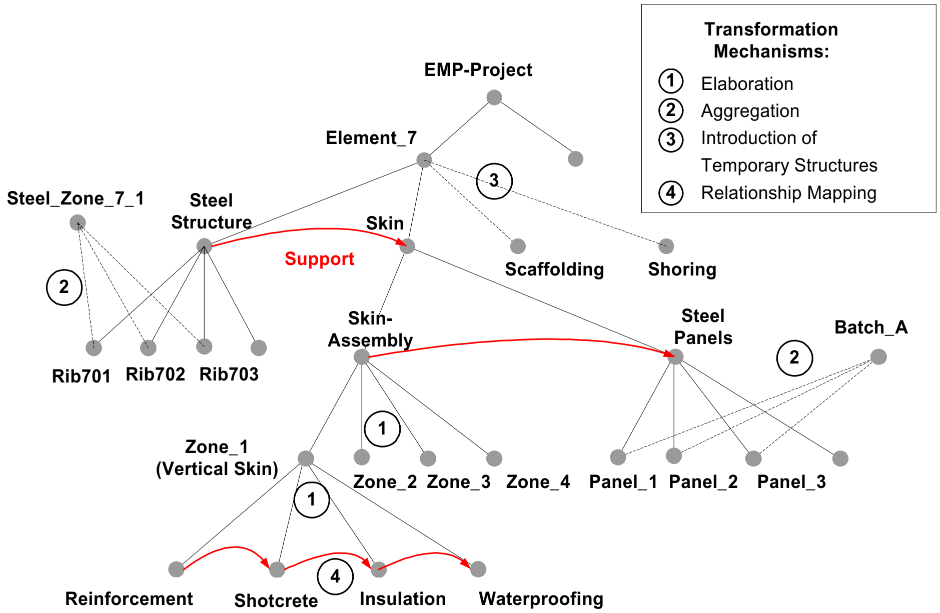

Fig. 3: Product model transformations from design to construction

a mathematical surface with the material information. The superintendent needed to plan the installation of the shotcrete in more detail. The activities he created would act on detailed skin components: reinforcement, waterproofing, insulation, and shotcrete. So he elaborated the product model accordingly. The breakup of a large component into zones is another example for elaboration type transformation.

3.2 Aggregation

In this mechanism, the components in the product model are combined to define new components. The architect designed the steel ribs as individual objects. The site superintendent, however, needs to combine a group of steel elements into one zone in order to accurately plan activities related to steel erection.

3.3 Introduction of temporary structures

Typically, temporary structures are not included in design documents or design-centric product models. However, they require resources for their installation and take up space for the duration of their use. Therefore, a construction planner needs to take the construction and dismantling of temporary structures into account when creating and evaluating a construction schedule. In the EMP, the general contractor created the shoring and scaffolding components using the product geometry and workspace constraints. Tools that create or configure temporary structures need to reason about the geometry as described in section 5.

3.4 Relationship mapping

The relationships between components can also vary in different views during the life cycle of the project. Whenever there is a change in the product model because of transformations, the underlying representations should be updated.

The planner needed to analyze the tolerance between the skin components to plan the installation sequence of the skin components. As the contractor elaborates the skin into components, the physical support relationships should be created automatically. We have implemented algorithms that can translate the relationships from design to construction using geometric reasoning.

Figure 4 shows our approach for product model transformations. Our research focuses on mappings from the design view to the construction view, although we are well aware that this is not the only possible transformation type. Since design always precedes construction, there is always a design-centric model before the other views.

4 Representation for multiple views

As the EMP illustrates, there should be multiple representations for certain components in the product model. Rosenman and Gero (1996) suggest that views should be able to represent a component with different composition hierarchies. Different graphical representations for a certain component will either have to be stored in each view, or need to be created with methods linked with that component.

It is widely accepted that AEC information should be represented in multiple views so that participants in a construction project can extract their views from the product model of the project and update the model after changes (Eastman and Siabiris 1995; Hannus and Pietilainen 1995). There have been various approaches to representing multiple views (Table 1). MacKellar and Peckham (1993) suggest that product models that support views can consist of a single or of multiple models.

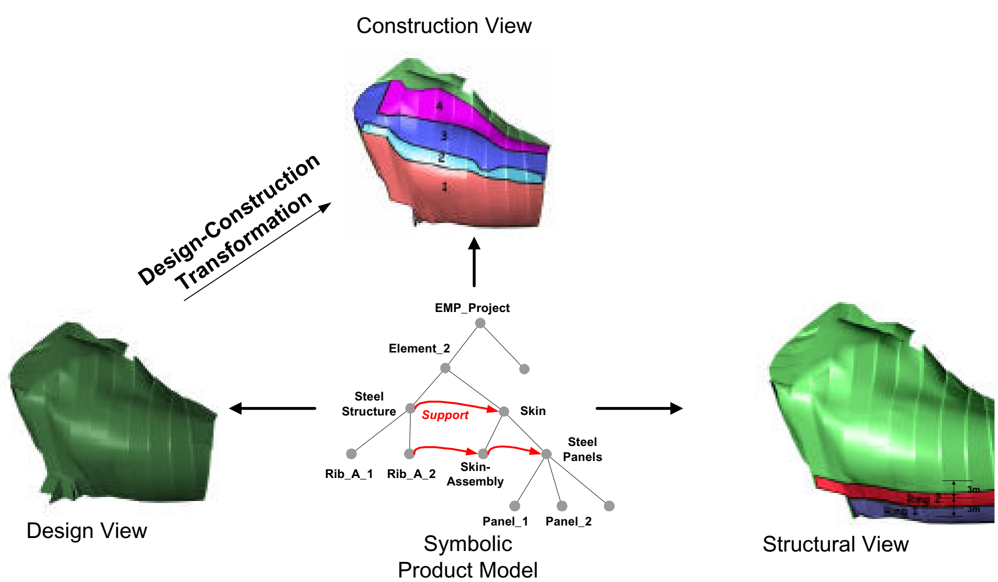

Fig. 4: Multiple view representation in the product model

Table 1: Approaches for multiple view representations

	Advantage	Limitation
Aspect Models (Van Nederveen and Tolman 1992)	Creates views from a single product model	Cannot change initial schema
P-C Approach (Howard and Phan 1995)	Provides methods to define product models and create multiple views	Fixed set of primitives No transformations
IFC (IAI 1998)	Provides a standard language for product models	No view definitions or transformations
EDM2 (Eastman and Siabiris 1995)	Provides database mechanisms for view changes	Limited to design phase

4.1 Static-schema models

Initial focus on multiple view representation has been on static-schema models. A schema is a template for a data model representation. Van Nederveen and Tolman (1992) define a kernel model and use aspect models to store view-specific information. The result is a set of models, each of which describes the building from a different viewpoint. They define the relationships between these aspect models. Although efficient during modeling, this approach is limited in updating the model, because it defines a static version of the product model rather than an evolving schema necessary to make the project information through design and construction.

The Primitive-Composite (P-C) approach (Howard and Phan 1995) is a data modeling technique that supports multiple views. Users define the primitives for the product model manually using a well-defined methodology. It is possible to aggregate the primitives to create composites. Using a selected set of primitives and composites, multiple views are created. However, the user needs to know beforehand how detailed the components should be, which limits the usability of the approach. In addition, each primitive can only have a single interpretation in this approach. Ongoing efforts towards Industry Foundation Classes (IFC) are standardizing the product model. However the IFC do not provide a mechanism for view definitions and transformations (IAI 1998).

4.2 Evolving-schema models

It is very cumbersome to map the product model manually on each a change in views. Consequently, there should be automated methods within the product model that support these transformations. The components of the product model should have methods that support not only the creation of new objects but also views of the product model that may differ in the level of abstraction and detail.

EDM-2 (Jeng and Eastman 1998, Eastman and Siabiris 1995) represents and supports translations between design views that evolve throughout the design process. Therefore, it is capable of model evolutions. A core model exists to reduce the number of maps required. EDM-2 is essentially a product database, grounded on a data model. It addresses fundamental database issues, such as the maintenance of data integrity; the defining of derivations and views; and the definition of a procedural language supporting model addition, deletion and modification. EDM-2 is implemented at the data level and does not, to our knowledge, specify operational transformations for construction.

5 Geometric reasoning

Figure 5 shows our geometric reasoning architecture. The user defines transformation rules and specifies items that create constraints for the system. Using the product model that is generated during design, the system reasons about the geometry to define the spatial relationships and extracts the features from the components to produce the construction view. The product model kernel is built on Industry Foundation Classes.

3D CAD models contain essential information to develop transformations. To transform between the different views of the product models, there must be efficient geometric reasoning techniques. The requirements for these techniques are the representation of spatial relationships between objects, the extraction of geometric properties and features, and the evaluation of constraints.

To decide on the layout for the shoring inside the structures of the EMP, spatial relationships between the shoring and the ribs, cranes and scaffolding must be represented. The layout is constrained by factors like the curvature of the ribs and workspace requirements. The structural engineer resolves the dimensions of the shoring and makes an update on the layout. At this point, the contractor needs to do time-consuming rethinking to evaluate the layout and consider its effects. Similarly, to decompose the shotcrete surface into zones, an automated system should consider the relationships between the scaffolding and the skin surface and the height and curvature of the skin. Construction process information affects the constraints. For example, the flow of work to install the skin is a constraint for the shoring layout.

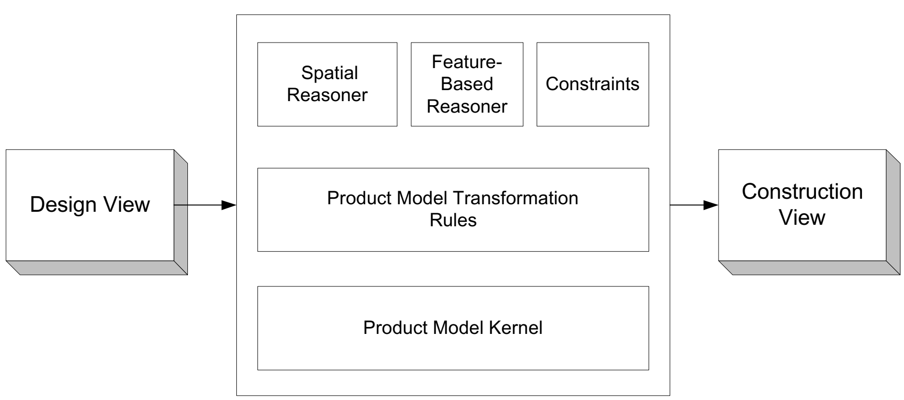

Fig. 5: Architecture for product model transformations

Previous research has defined techniques for geometric reasoning in different industries. For example, in the manufacturing industry, CAD systems are widely used as planning tools, as in assembly and process planning (McMahon et al. 1998).

The complex geometry of the parts and the assemblies are abstracted using features that store the product's important characteristics and associate them with engineering knowledge. Using feature-based modelers, or feature extraction algorithms, it is possible to plan and reason about the geometry of each feature. Ongoing efforts try to define a similar scheme for architectural design (Leeuwen and Wagter, 1998). We have tested the reasoning techniques used in feature extraction algorithms to reason about the properties of a geometric model.

In construction, the GRID research project developed a qualitative geometric-reasoner for spatial, temporal, and logical reasoning about 3D geometry (Chinowsky and Reinschmidt 1995). Qualitative spatial relationships are used to abstract the spatial relationships between components and reason about the geometric model (Clementini et al. 1997). Quantitative distances are converted to relationships like *after, on-top,* and *contains*. This directional information defined in one dimension is generalizable to multi-dimensional models. However, these research efforts simplified the geometry of the components to basic primitives, which is not sufficient for real world construction projects.

6 Conclusions and future work

This paper described ongoing research to define a methodology to transform product models from design to construction using product model transformations. We are focusing on geometric reasoning techniques needed for these transformations.

This research is a part of the effort to automate generation of 4D production models based on design-centric product models. We are implementing these mechanisms using the Object ARX development environment in Autodesk Mechanical Desktop and the Construction Method Modeler (CMM), an automated construction process planner (Fischer and Aalami, 1996).

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