Feature-based Product Modeling for Building Construction

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Summary

Current building product models explicitly represent components, attributes of components, and relationships between components. These designer-focused product models, however, do not represent many of the design conditions that are important for construction, such as component similarity, uniformity, and penetrations. Current design and construction tools offer limited support for detecting these construction-specific design conditions. This paper describes the ontology we developed using the manufacturing concept of features to represent the design conditions that are important for construction. The feature ontology provides the blueprint for the additions and changes needed to transform a standard product model into a construction-specific product model. The ontology formalizes three classes of features, defines the attributes and functions of each feature type, and represents the relationships between features explicitly. The descriptive semantics of the ontology allows practitioners to represent their varied preferences for naming features, specifying features that result from component intersections and the similarity of components, and grouping features that affect a specific construction domain. A software prototype that implements the ontology enables practitioners to transform designer-focused product models into feature-based product models that represent the construction perspective.

1 Introduction

Recognizing the design conditions that affect constructability is essential to developing cost-effective designs. Facility designs often contain design conflicts, errors, omissions, or implicit constraints that require rework or re-design, limit the use of effective construction methods, cause improper construction sequencing, and reduce productivity, ultimately leading to construction delays and cost overruns. While there are many factors that affect constructability, design-specific factors are particularly important because they have the greatest influence on construction cost (Paulson 1976). Research has shown that approximately 75% of construction costs are decided at the design stage (Paulson 1976) and that approximately 50% of construction productivity and quality problems are attributable to inadequate design (BRE 1981, Barber et al., 2000). This research focuses on understanding and modeling the design conditions that affect design constructability and increase construction costs.

A variety of design conditions may affect constructability, including the horizontal and vertical layout of elements, distances between elements, dimensions, tolerances, spacing, modularity, connection details, repetition, similarity, uniformity, and use of standard sizes (Fischer 1991, Hanna and Sanvido 1990, ASCE 1991). These design conditions are important in a variety of project management functions, including cost estimating, method selection, scheduling, constructability reviews, value engineering, and productivity analysis. Many of these design conditions occur frequently from project to project and are critical to a design's constructability in a variety of construction domains. For example, modularity, similarity, layout, and standard sizing are important for the constructability of walls, ductwork, piping, and columns in building construction, and girders and trusses in bridge construction. Today, construction professionals spend significant amounts of time analyzing and interpreting a facility design to identify these construction-specific design conditions. Current design and construction tools offer limited support beyond simple 3D conflict detection for detecting these construction-specific design conditions. To provide product models that represent the construction perspective, construction professionals need a vocabulary to describe the design conditions that are important to them, and tools to help identify these design conditions in a given 3D model.

This paper describes different aspects of completed and ongoing research that is focused on developing an ontology (i.e., a computer-interpretable vocabulary) using the manufacturing concept of *product features* to represent construction-specific design conditions. Features are used extensively in manufacturing to describe the geometric forms or entities in a product model that are important in some aspect of the manufacturing process (i.e., manufacturability evaluation and flexibility analysis) (Cunningham and Dixon 1988). Several researchers have recognized the potential benefits of a features representation for civil engineering artifacts (e.g., Fenves 2001, van Leeuwen 1999), but these efforts have primarily focused on representing building components and do not represent features of design elements that affect construction. This research aims to extend and articulate the concept of features for building construction with the goal of providing a consistent, unambiguous, and computer-interpretable representation.

This research leverages recent progress in the development of Industry Foundation Classes (IFC's), the primary product model exchange standard for the architecture, engineering, and construction (AEC) industry (IAI 2001). The IFC's define the element classes and properties, geometry, and the topological relationships between elements. Many architectural modeling applications can export IFC-based product models, enabling the sharing of these semantically-rich product models with other software applications. IFC-based product models provide the foundation for interpreting the existence of product features independent of the CAD application that created the 3D model.

The following sections first describe two case studies that illustrate the design features that are important for two construction domains. Then, subsequent sections describe different types of features currently represented in the ontology, including specific instances of features from the case studies. Finally, the specific validation studies conducted to date will be discussed.

2 Case Studies

This section describes two case examples that illustrate the different types of design conditions that affect construction. These case studies were selected because they represent sufficiently different construction domains and yet illustrate unique and common design conditions. The case examples shown in Figure 1 highlight several design conditions that affect drywall (Figure 1a) and concrete (Figure 1b) construction.

The case studies show that construction professionals consider similar design conditions (e.g., 'component height'), use different terms to describe the same design condition (e.g., 'wall-beam intersection' and 'structural penetration'), and have different preferences for describing the concept of component similarity (e.g., '75-100% of wall heights and types are similar' and '50-75% of column shapes are similar'), uniformity (e.g., 'uniform column location' and 'non-uniform column spacing'), and clustering (e.g., 'clustering of similar walls' and 'clustering of uniform and similar columns').

The case studies also show that design conditions can be based on:

- properties of components (e.g., the 'curvature' and 'height' of the wall),
- groupings of components (e.g., the 'grouping of walls' based on component similarity),
- intersections of components (e.g., the 'structural penetration' resulting from the intersection of the wall and beam), and
- properties of component intersections (e.g., the 'orientation' of wall turns).

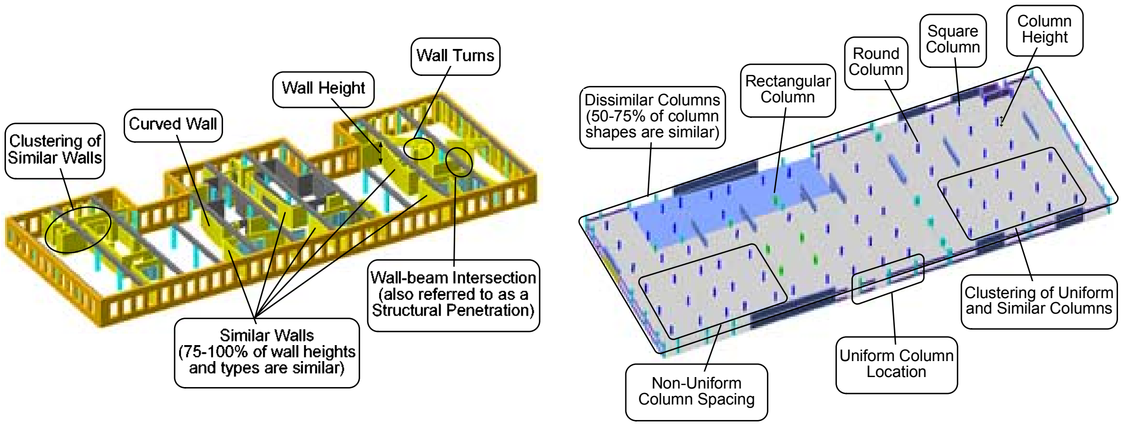


Figure 1a: Drywall scope for an office project highlighting some of the design conditions that affect drywall construction.

Figure 1b: Concrete column scope for a 2-story parking structure project highlighting some of the design conditions that affect concrete construction.

Figure 1: Case studies of drywall and concrete construction.

It is too time-consuming to manually identify all the project-specific design conditions in a given design. Consequently, many constructability issues go undetected until field installation, which often results in rework, re-design, or decreased crew productivity, ultimately leading to higher costs and a sub-optimal project performance. To provide construction-specific product models, construction professionals need a vocabulary to describe construction-specific design conditions and tools to identify them in a given 3D model.

3 Feature Ontology

This research aims to develop a construction-specific feature ontology that is flexible enough to represent different construction perspectives and formal enough to support a consistent and unambiguous representation. Characterizing construction-specific design features requires an understanding of design function, the physical behavior of elements, and the interaction between elements. We have tried to capture the subtleties for how practitioners think about the design to understand the underlying characteristics of what are often abstract concepts (e.g., the concept of uniformity). The feature ontology classifies three types of features, defines the attributes and functions of each feature type, and represents the relationships between features explicitly (Staub-French et al. 2003). We implemented the feature ontology in a software prototype called Feature Generator (FeaGen) to support feature-based cost estimation.

The case studies demonstrate that there are different types of features. Features can be components (e.g., a 'wall'), features can emerge from intersections of components (e.g., the feature 'turn' emerges from intersections of walls), and features can emerge from groupings of components based on their similarity (e.g., 'wall similarity' based on similar wall heights). Consequently, we have classified features into the following types:

(1) *Component Features:* Features that result from components in an IFC-based building product model, such as walls and columns.

(2) *Intersection Features:* Features that result from intersections of component features, such as penetrations and turns.

(3) *Macro Features:* Features that result from pre-specified combinations of other features, such as similarity and uniformity of component features.

Each feature type has different attributes that allow construction professionals to represent feature instances according to their preferences.

3.1 Component Features

As defined above, component features are simply components that would typically be found in a building product model. Several researchers use features to represent the building components that are important in the design process similar to this research (e.g., Clayton et al. 1996; van Leeuwen 1999). The main distinction here is that we are referring to these components as features that are important for construction, which facilitates consistency in describing construction-specific design conditions.

In the feature ontology, the common attributes of component features include the same attributes defined by the IFC's, as well as the following:

(1) *Feature Set:* The practitioner's preference for the features that affect a specific component's construction costs. For example, the drywall contractor in the case example would include 'wall-beam intersections' and 'turns' in the feature set for walls.

This attribute allows construction professionals to specify the features that are important for a particular construction domain and a particular construction perspective. We have focused on the application domain of cost estimating but this structure is generally applicable to a variety of project management perspectives, such as constructability reviews, value engineering, and productivity analysis.

3.2 Intersection Features

Cunningham and Dixon (1988) formalize 'intersection features' to represent features that emerge from intersections of primitive and add-on features (e.g., corners). We extend the definition of 'intersection features' to represent building designs by defining intersection features as the intersection of component features. The attributes of intersection features give practitioners the ability to create or customize instances of intersection features as they see fit.

The attributes of intersection features are based on the attributes used by the IFC's to represent the connections between components (IAI 2001). Although the IFC's represent the connections between components explicitly, they do not provide a way to filter the component connections that are important for construction. For example, the wall's connection with the ceiling and floor was not a critical design feature to the drywall contractor while the wall's connections to other walls ('wall turns') and to the beam ('structural penetration') were important because these connections impact drywall installation and cost. Moreover, some component connections are not explicitly represented in IFC-based product models because the designer does not intend for the components to be connected. For example, the connection between the wall and the beam emerges based on the architectural and structural designs. We instantiate these important component connections as intersection features.

The two attributes of intersection features are:

(1) *Relating Component:* The component class that is being considered. From the case examples, the practitioners considered 'wall' and 'column' components. This attribute is named 'RelatingElement' in the IFC's.

(2) *Related Component(s):* The component classes of the intersecting components for the 'Relating Component.' For example, to represent the 'wall-beam intersection' feature, the practitioner would specify 'wall' for the 'Relating Component' and 'beam' for the 'Related Components.' This attribute is named 'RelatedElements' in the IFC's.

The attributes of intersection features allow construction professionals to represent their preferences for what component intersections are important for a particular construction domain and how to name the component intersections.

3.3 Macro Features

Cunningham and Dixon (1988) define ‘macro features’ as pre-specified combinations of primitives (e.g., boxes). We define macro features as pre-specified combinations of other features. We have started to define the attributes necessary to describe specific macro features, which currently includes component similarity, uniformity, and clustering.

3.3.1 Component Similarity

Many researchers have recognized the importance of component similarity as a critical design feature in developing constructable designs (e.g., Hanna and Sanvido 1990 and Fischer 1991). However, the approaches to date have either represented this concept implicitly in computer code or vaguely in prescriptive statements. For example, Hanna and Sanvido (1990) represent this concept in guidelines that specify “conventional form systems…can handle variation of column wall/size and location.” The ontology represents the concept of component similarity quantitatively, explicitly, and consistently.

The attributes formalized to represent component similarity are:

(1) *Component Grouped:* The component that is being evaluated for similarity. In the case examples, ‘walls’ and ‘columns’ are being evaluated for component similarity.

(2) *Direction:* The direction for which component similarity will be assessed, which can be either ‘horizontal’ or ‘vertical.’ The horizontal direction represents similarity across a single floor. The vertical direction represents similarity across floors. In the case examples, the drywall and concrete practitioners evaluated similarity in the horizontal direction.

(3) *Component Variation:* The overall variation of the components allowed to achieve component similarity. This attribute is needed because practitioners have different preferences for the degree of similarity that must be achieved for component similarity to exist. In the drywall case example, the contractor preferred that 75-100% of the walls have similar heights for component similarity to exist.

(4) *Similar Component Properties:* The component properties (or property) of the component grouped that will be compared to determine whether the components are similar. In the drywall case example, the contractor analyzed the properties ‘height’ and ‘type’ to assess the similarity of wall components.

(5) *Property Variation:* The variation in the value for the similar component property allowed to achieve similarity. For example, if a practitioner specifies 2” for the property variation, then the practitioner views wall #1 as similar to wall #2 if its height is at most 2” shorter or taller than wall #2.

The next two sections describe some of the research issues associated with representing the design features uniformity and clustering. This part of the research is part of an on-going research project and has not been implemented and tested to date.

3.3.2 Uniformity of Components

Uniformity is often cited as a key design feature in design constructability (e.g., ASCE 1991) and in method selection (e.g., Hanna and Sanvido 1990). In practice, the concept of uniformity is often used interchangeably with similarity, which creates ambiguities when creating computer-based methods for design interpretation. A key aspect of this research is the development of definitions and abstractions of uniformity that distinguish this concept from similarity without limiting its application.

The case studies showed two examples of component similarity: 1) similarity of wall heights and types, and 2) similarity of column shapes (Figure 1). In these cases, the building components are compared and evaluated individually based on their properties to assess the degree of commonality. Although we described this as an evaluation of similarity, we could have just as easily considered this to be an issue of uniformity without violating the intent of this design concept. Conversely, the two examples of uniformity could not be confused with similarity. The examples included: 1) uniformity based on column spacing and 2) uniformity based on column location (Figure 1). These examples of uniformity could not be confused with similarity and therefore can be represented unambiguously. Therefore, the case studies help to differentiate the concepts of uniformity and similarity.

Our contention is that the similarity of building components, as a computer-interpretable design feature, should be assessed based on the specific properties of the building components being considered. If the design condition of interest requires a comparison of the building component properties for degrees of commonality, then the design feature of interest is similarity. To assess the uniformity of building components, our contention is that this feature should be represented and assessed based on the pattern, layout or location of building components. We believe that this distinction will help to avoid inconsistencies and ambiguities in representing these design features, and enable computer-based support for identifying them in a given 3D model.

3.3.3 Clustering of Components

The notion of clustering is important for construction because the adjacencies of similar and uniform building components can play a critical role in the effective installation of these components. It is not sufficient to know if the building components are similar and have uniform spacing, practitioners also need to know if these similar building components are in the same area. The research issues associated with defining a ‘cluster of components’ revolve around the representation of component adjacencies, relative locations, areas, and degrees of similarity and uniformity.

4 Creating Project-Specific Feature-based Product Models

As stated previously, we implemented the feature ontology in a software prototype called Feature Generator (FeaGen). FeaGen transforms an IFC-based product model into a feature-based product model that represents the construction perspective (Figure 2). First, practitioners represent the relevant intersection features and customize component similarity in FeaGen in user-customizable Feature Specification Templates (Section 4.1). Second, FeaGen uses the generic construction-specific features to create a project-specific feature-based product model that represents the features that are important to that practitioner (Section 4.2). We created another software prototype called Activity-based Cost Estimating (ACE) that uses the feature-based product model to generate and maintain construction cost estimates (Staub-French 2002).

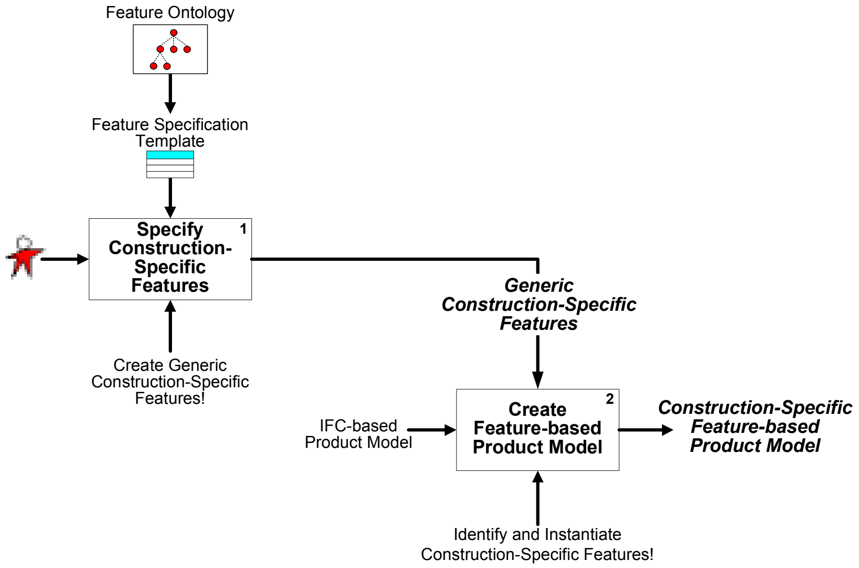
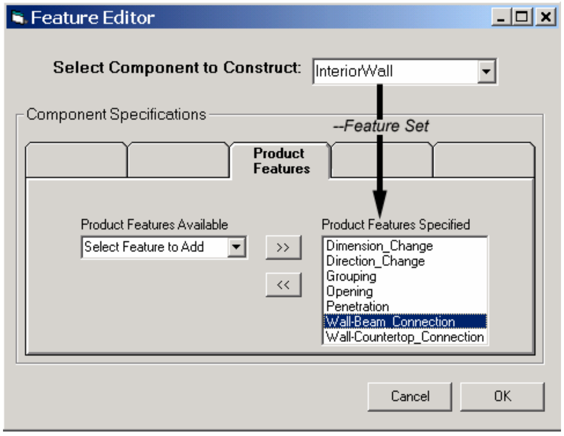


Figure 2: Overview of two-step process for creating construction-specific feature-based product models.

4.1 Specify Construction-Specific Features

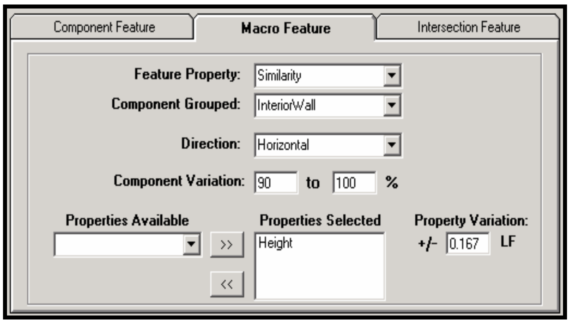
Practitioners use Feature Specification Templates to specify component intersections and to define component similarity based on their perspective and the construction domain they are considering. FeaGen represents these features generically so that they can be reused from project to project. Practitioners also specify the sets of features and properties that affect a specific component's construction in this step. Figure 3 shows example Feature Specification Templates for specifying the sets of features that are important for a particular component (Figure 3a), and for specifying component similarity (Figure 3b). Based on these input specifications, FeaGen knows what features and properties affect the construction of a specific type of component and how to represent component similarity according to the practitioner's preferences.



Select Component to Construct: InteriorWall

Product Features Specified:
Dimension_Change
Direction_Change
Grouping
Opening
Penetration
Wall-Beam_Connection
Wall-Countertop_Connection

Figure 3a: Feature Specification Template showing an example feature set for walls.



Feature Property: Similarity
Component Grouped: InteriorWall
Direction: Horizontal
Component Variation: 90 to 100 %
Properties Selected: Height
Property Variation: +/- 0.167 LF

Figure 3b: Feature Specification Template showing an example specification for the similarity of walls.

Figure 3: Examples of Feature Specification Templates used to collect practitioners' preferences for defining features for a specific construction domain.

4.2 Create Construction-Specific Feature-based Product Model

FeaGen analyzes the geometry of components and the topological relationships between components in standard building product models to identify the design features that affect construction. Identifying component features is a relatively straightforward task given that these elements are represented explicitly in the input IFC-based product model. The challenging part of creating feature-based product models is analyzing the design to infer the existence of intersection and macro features.

4.2.1 Identify Intersection Features

To identify intersection features, FeaGen reasons about the topological relationships between components, which are represented in different ways depending on the intersecting components. Some relationships between components are represented explicitly in IFC-based product models. For example, the connections between walls and doors and between two walls are explicit in an IFC-based product model because the architect intends for these components to be connected. Consequently, to determine whether the components are intersecting, FeaGen queries the objects connected to the component in the 'RelatedElements' attribute to find the intersecting components, and then analyzes the 'TypeOf' attribute to identify the intersecting components that have the required component type.

In contrast, some relationships between components are implicit in IFC-based product models. For example, the connection between the wall and the beam is implicit because it emerges based on the architectural and structural designs. Consequently, conflict detection mechanisms are needed to determine if these components are intersecting. In the current implementation of FeaGen, users need to identify these types of component intersections manually.

4.2.2 Identify Component Similarity

To identify component similarity, FeaGen reasons about the properties of building components of the same type to determine whether the property values are similar. FeaGen identifies the relevant instances of building components in the IFC-based product model based on the component class specified in the 'component grouped' attribute. If "horizontal" is specified in the 'direction' attribute, FeaGen evaluates the building components on a single floor. If "vertical" is specified in the 'direction' attribute, FeaGen evaluates the building components on all the floors. Then, FeaGen analyzes each property of the building component specified in the 'similar component properties' attribute. FeaGen cycles through each building component instance and compares it to the previous one to determine whether the components are similar. FeaGen compares the property values to determine whether the variation is acceptable based on the practitioner's preferences in the 'property variation' attribute. If the value of the component property is within an acceptable range, FeaGen considers that component to be similar and adds it to a collection containing the similar components. After FeaGen has evaluated all the properties of all the components, it calculates the percentage of similar components by dividing the number of similar components collected by the number of components evaluated. If the percentage calculated is within the range specified by the estimator in the 'component variation' attribute, FeaGen considers the components to be similar.

FeaGen generates a project-specific feature-based product model that explicitly represents the features that are important for construction from a particular practitioner's perspective. The feature ontology provides the blueprint for the additions and changes needed to transform an IFC-based product model into a construction-specific product model.

5 Validation

We performed a charrette test (Clayton et al. 1998) and three retrospective tests to demonstrate the power and generality of the feature ontology (Staub-French 2002). The validation tests do not include the design concepts of uniformity and clustering as these feature representations have not been implemented and are part of an on-going research project.

To demonstrate the power of the ontology, we tested the utility of the construction-specific feature-based product model for cost estimating using the prototype cost estimating system ACE, which was developed as part of this research. ACE uses the feature-based product model as the input product model for cost estimating. We used ACE to demonstrate that the feature-based product model helps estimators to generate and maintain cost estimates more accurately, consistently, and quickly than IFC-based product models. To assess the accuracy of the estimates, we evaluated the level of completeness of estimates generated by 13 estimators using ACE and compared them to estimates generated by the same estimators using Timberline's state-of-the-art Precision Estimating (PE) software (Timberline 2001), which is an industry standard for cost estimating software. We used level of completeness to measure the extent to which estimators accounted for the cost impacts of features explicitly. We defined a theoretical ideal to represent the "most complete" estimate for each test case. These tests showed that estimators using ACE generated estimates that are 86% complete while the same estimators using state-of-the-art software tools generated estimates that are 68% complete. For the maintenance of cost estimates for specific design changes, ACE helps estimators to maintain estimates that are 92% complete whereas the state of the art software tools help estimators to maintain estimates that are 29% complete. The charrette test also demonstrated that practitioners using ACE were able to more consistently identify the correct cost impact and identify cost impacts 17% faster using ACE.

To demonstrate the generality of the feature ontology, we modeled costs for two different component types in three retrospective test cases. Different features and feature properties impact costs for these two component types. Table 1 shows the different features represented in the feature ontology for each component type. We also demonstrated that 13 different estimators could specify their preferences for representing the features that affect construction costs. The ability of practitioners to represent different features for different component types and different preferences for defining features demonstrates the generality of the feature ontology.

Component Features	**Intersection Features**	**Macro Features** *(Component Similarity)*
Walls	Turns	Similarity of Height
	Openings	Similarity of Width
	Penetrations	Similarity of Type
	Wall-Beam Intersections	
	Wall-Countertop Intersections	
Columns	Column-Slab Intersection	Similarity of Height
		Similarity of Width
		Similarity of Length
		Similarity of Shape

Table 1: Features represented in the feature ontology for two test cases on walls and columns.

6 Conclusions

This paper describes the ontology of features we developed to represent the design conditions that affect building construction. A key consideration in developing this ontology was providing a consistent, unambiguous, and computer-interpretable representation of features. The ontology allows practitioners to represent their varied preferences for naming features, specifying features that result from component intersections and the similarity of components, and grouping features that affect a specific construction domain. We implemented the ontology in a computer prototype to demonstrate that it facilitates the automatic detection of many construction-specific design features. Our tests show that for the application domain of construction cost estimating, feature-based product models improve the accuracy, efficiency, and consistency of the cost estimating process.

Automating the generation of construction-specific feature-based product models has the potential to significantly improve the efficiency of the construction process. Today, construction professionals spend significant amounts of time analyzing and interpreting a facility design to identify the design features that affect productivity, method selection, scheduling, and constructability. If these design features could be identified automatically, practitioners could provide prompt feedback to designers on the specific features that are impacting construction. As a result, project teams could perform what-if analyses on different designs and explore a larger variety of design alternatives to identify the lowest cost design. Hence, project teams can leverage feature-based product models to develop more cost-effective and constructable designs in less time.

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