ANALYZING BUILDING INFORMATION USING GRAPH THEORY

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ABSTRACT

The networks of interdependencies between elements in building projects, referred to as the project topology, are often complex and difficult for project teams to comprehend. It is hypothesized that a graph-based model of the project topology can be based on existing data in Building Information Models (BIM), facilitating the application of graph-theoretic algorithms to analyze this topology. The objective of this study is to propose an outline for the synthesis of BIM and graph theory. This synthesis is expected to contribute to the development of new tools for representing, managing and analyzing the design of building projects.

KEYWORDS

Design Management, BIM, Graph Theory

INTRODUCTION

The significant deviations from client objectives such as cost and performance that occur in many building projects indicate a need for a more rigorous design process (Love & Li, 2000; Manavazhi & Xunzhi, 2001; Moselhi, Leonard, & Fazio, 1991). Networks of interdependencies between elements in the project, such as requirements, building components and construction tasks, often create knock-on effects that magnify the impact of local deviations. These networks, referred to here as the *project topology,* are usually an incidental byproduct of the design process, and are difficult for design teams to understand, leading them to make decisions with unintended consequences.

Modeling the topology of a building project and effectively managing and analyzing it is challenging because projects have many interrelated aspects: a user requirement affects the attributes of building components, which in turn affect other related components as well as the activities required to construct these components. Moreover, projects constantly evolve, as new elements and relationships are added. They thus require a flexible model of the project topology, in which one can easily define new elements. Although challenging, the modeling of building project topologies is essential for the support of design processes, since decisions often affect a large number of components. A holistic systems model of projects is required, containing representations of all their elements, as well as tools that support the analysis of the project's topology.

Methods that provide a holistic view of complex engineering projects in order to support their design and development have been the focus of research in systems engineering (U.S. Department of Energy, 2008). Systems engineering is an approach that deals in particular with the definition of user requirements and their conversion into design specifications; on the integration of project design and verification that it meets user needs; and on the support of decision-making and risk management by the project team. The complexity of building projects appears to justify the application of Systems Engineering methodologies in their design. Building projects display both physical complexity, as reflected by the large number and variety of building components they contain, as well as combinatorial complexity, as reflected by the different, often competing, goals, requirements and stakeholders involved in projects. While systems engineering methods have been studied in the context of construction planning (e.g. Austin et al.. (2000)), they have been relatively absent from studies on building design.

The objective of this study is to propose an outline for the synthesis of Building Information Modeling (BIM) and graph theory, bringing together the two different modeling approaches – the first of which focuses on the modeling of project elements as data-rich, parametric 3D objects, while the second focuses on the modeling of networks of connected elements. Such a synthesis is the first step in the definition of a model of building project topology that can facilitate the development of new tools for representing, managing and analyzing the design of buildings.

BUILDING INFORMATION MODELING

Studies on the representation of building projects for design management have in recent years focused on the development and implementation of Object-Oriented (OO) models of projects, called

Building Information Modeling (BIM). These models contain objects that represent real-world project elements such as components in the design. BIM objects are organized into classes, and often have complex attributes (such as the cost of a component) which are a product of other attributes (such as the component's type, dimensions and materials). BIM, similar to other OO models, has mainly focused on object handling: the definition of the values of the objects' attributes, and the dynamic manipulation of these values. These models also contain valuable information on the relationships between project elements. However, they do not explicitly represent this information in a systematic way, and it therefore remains largely hidden and unused (Boeykens & Neuckermans, 2008; Haymaker, 2006). Thus, BIM tools currently lack, for the most part, the ability to represent the topology of networks of project elements.

In addition, current BIM tools display a lack of integration and a lack of adaptability. In spite of efforts that have been made to integrate different models of building projects through the development of standards for data interchange such as the Industry Foundation Classes (IFC) standard (buildingSMART, 2013), the integration of project information is not well supported by current tools. Project teams still have to rely on cumbersome and labor-intensive ad-hoc solutions to fully integrate the data (Halfawy & Froese, 2005; Hartmann, Fischer, & Haymaker, 2009). For example, the integration of information in design and in building programs is still very limited.

It is currently also very difficult to fully update construction project models following changes in the projects. The tools used for the design and planning of projects are not sufficiently adaptable and do not work well in a dynamic environment (Haymaker, Kunz, Suter, & Fischer, 2004; Hegazy, 1999). One technology which has been introduced in BIM tools for that purpose is parametric modeling, which applies predefined parametric relations and constraints to objects in the model. These objects are manipulated by the user by changing the values and relations of the parameters, while the BIM tool automatically maintains the predefined constraints. However, parametric modeling technology is limited by the difficulty of capturing tacit knowledge and interpreting it into explicit geometric and other relationships, which a system can understand (Lee, Sacks, & Eastman, 2006). The application of parametric technology has therefore generally been limited to the definition of one or two components at a time and in the same discipline, and it has not been widely used to integrate the work of multiple disciplines (Haymaker, 2006).

GRAPH-BASED MODELS

BIM has, so far, mainly focused on the development of objects with complex attributes and their manipulation (Halfawy & Froese, 2005). We hypothesize that existing data in BIM regarding the relationships between project elements can be used to develop a system model of the project. Such a model can be based on the use of graphs to represent the topology of building projects, and on the application of graph-theoretic algorithms to analyze and optimize this topology (Isaac & Navon, 2008, 2009). Graph database models, in which data structures are modeled as graphs, flourished in the information management community in the eighties and early nineties, in parallel to OO models, before their influence gradually faded. More recently, the need to manage information with inherent graph-like nature has brought back their relevance, and a new wave of applications for graph databases has emerged (Angles & Gutierrez, 2008).

Graph-based models are in general the primary approach to represent complex systems with a large number of highly interconnected elements (Boccaletti, Latora, Moreno, Chavez, & Hwang, 2006). However, the use of graph-based representations of the information contained in BIM has been, so far, sporadic and limited to specific domains such as:

- The representation of rooms and physical connections between building components for building energy simulation (C. van Treeck & Rank, 2007).
- The representation of spaces and openings for accessibility analysis (Eastman, Lee, Jeong, & Lee, 2009).
- The representation of connections between rooms (such as doors and windows) for space planning (Wessel, Blumel, & Klein, 2008).

In a graph-based model of building projects, nodes represent the project elements (for instance the components in the design), and links between the nodes represent the relationships between elements (for instance the relationship between a component in the design, and a requirement in the building program which the component satisfies). Formally, the graph $G = (N,L)$ consists of two sets N and L, such that $N \neq \emptyset$ and L is a set of pairs of elements of N. The elements of N are the nodes of the graph G representing project elements, while the elements of L are its links representing the relationships between elements. This is a strong approximation, since it means translating the interaction between two elements, which usually depends on time, space and other details, into a simple binary number: the existence or not of a link between the two corresponding nodes. Some information can be added by defining a weighted link, representing the strength of the relationship. This information can nevertheless be useful for representing the topology of building project design. A graph-based model, representing the project topology, is in many cases likely to facilitate the integration and adjustment of the reduced amount of information contained within it with greater ease than BIM.

INTEGRATING BIM AND GRAPH THEORY

The objective of this stage of the present study is to propose an outline for the synthesis of BIM and graph theory, bringing together these two modeling approaches in order to create a model of the topology of building projects. The information on project elements and their relationships, used to define the graph-based model, will be extracted from databases that will include BIM. The ability to automatically extract information on the relationships between components from BIM has, for example, been demonstrated in Nguyen, Oloufab, & Nassar (2005) and Paul & Borrmann (2009). The graph-based model will, however, contain a reduced amount of information on these components, in comparison with the databases from which this information is extracted. BIM objects with complex attributes and parametric relations will be simply represented as nodes in a graph with links to other nodes. Such a model can facilitate:

1. An integrated representation of information on different project aspects (such as requirements, design and construction planning) in a single model.
2. The adjustment and updating of data through the application of graph transformation rules.
3. The analysis of the project topology through the application of graph theoretic algorithms.

Representation: The use of a graph-based model enables moving to a higher-level abstraction, from a representation at the object level to a representation of the entire project (Figure 1). Graph-based models represent systems as networks of relations, emphasizing data interconnection. They are therefore applied in areas where information about data interconnectivity or topology is more important, or as important, as the data itself.

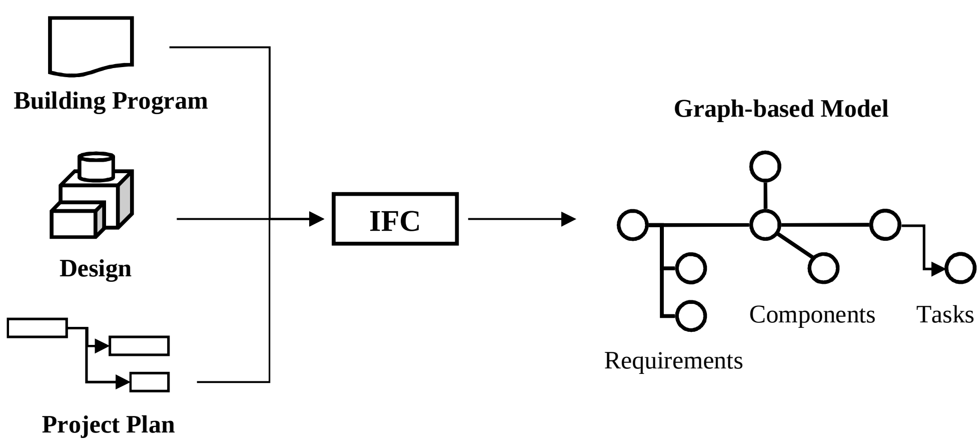


Figure 1 – Graph-based representation of building project

The use of a graph-based model to represent building projects enables the integration of different project aspects which are currently often defined in separate models (corresponding definitions in the IFC system are added in brackets):

- The building program – containing the project requirements (IfcProperty, IfcPropertySet) specified for the planned spaces (IfcSpace) in the building.
- The design – containing building components (IfcElement) and subsystems (IfcSystem, IfcElementAssembly).
- The project plan – containing planned construction tasks (IfcTask), and resources (IfcResource) allocated for the tasks.

Each IFC object is defined as a node in the graph. The relative ease of integrating such disparate aspects in the graph-based model is due to the fact that relationships between elements belonging to different aspects are defined as simple links between nodes. These relationships can also be extracted from BIM databases where they are defined as IfcRelationship objects. Each such object is then defined as a link in the graph.

Adjustment: Graph-based models are appropriate for representing systems such as building projects, to which new types of elements and relationships are added over time. The incorporation of new types of data can be ensured through the application of Graph Transformation (GT) rules (Isaac & Navon, 2009). GT is a technique for automatically implementing changes in graphs through predefined rules (Heckel, 2006). The GT rules specify how the graph should be built, and how it can evolve. This can also make it easier to extend BIM beyond component design, to the modeling of other aspects such as user requirements, resource allocation and maintenance activities. Using GT rules, the model can be adjusted to include new elements, as well as changes in existing elements in the project. The use of GT rules ensures that the correctness and consistency of the model is maintained.

Analysis: The application of graph-theoretic algorithms in the model can enable the analysis of the topology of a building project, and of issues that simultaneously involve a large number of elements. Numerous such algorithms exist for an automated or semi-automated analysis of complex systems consisting of large networks of elements (Figure 2).

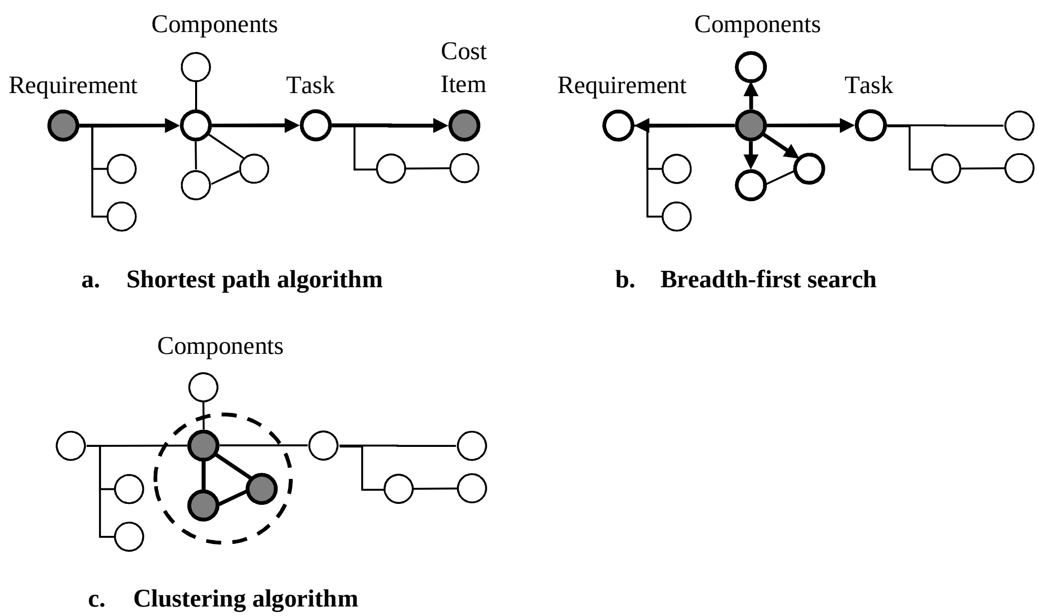


Figure 2 – Application of graph-theoretic algorithms

Algorithms that are run in the graph-based model can refer directly to the project topology. For example:

- The application of a shortest path algorithm to identify the elements through which one element (such as a requirement) is linked with another element (such as a cost item).
- The application of a breadth-first search of neighboring nodes to identify all the elements directly related to a specific element (for example, those connected to a specific building component).
- The application of a clustering algorithm to identify certain sub-graphs (such as a subsystem of relatively closely connected components in the design).

Such algorithms can reduce the considerable amounts of time project team members currently spend manually sifting through large volumes of data in order to analyze it. The conversion of existing BIM data into graph-based representations, based on the IFC definitions of this data, can thus facilitate a different approach to the modeling, management and analysis of building project data (Table 1).

Table1 – BIM and graph-based modeling of building projects

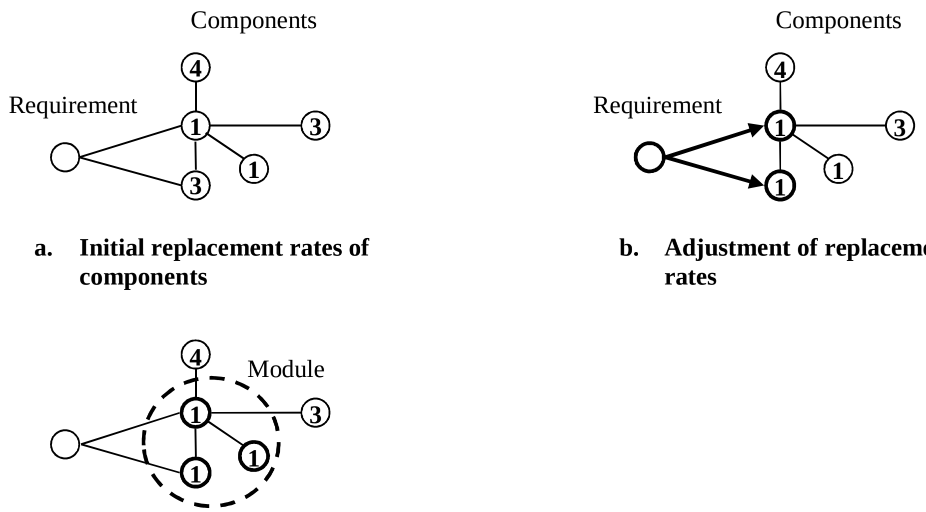
	BIM	**Graph-based modeling**
Component representation	Objects with attributes	Nodes
Relationship representation	Complex OO relationships (e.g. aggregation, association, etc.)	Binary or weighted links; Directed or undirected links
Adjustment	Parametric modeling	Graph Transformation rules
Analysis	Rule-based OO algorithms (e.g. clash detection, quantity takeoff, etc.)	Graph-theoretic algorithms (e.g. shortest path, breadth-first search, clustering, etc.)

EXAMPLE

The following example demonstrates the feasibility and benefits of the application of graph-theoretic algorithms in a graph-based model of building project design.

The objective in this example is to support the design of buildings that can be gradually adapted throughout their use. This is done by systematically separating building components whose replacement occurs at different rates, into modules that can be easily disconnected (Isaac & Sadeghpour, 2012). These components are otherwise connected through physical or functional relations. Components that satisfy the same user requirement are functionally connected, since changes over time in the requirement may involve changes in these components or their replacement. The definition of the requirements in the building program may thus have an impact on the definition of the modules in the design. For example, the requirements in one project may justify the design of a partition wall as a single module which can be easily replaced, while in another project they may justify the design of the wall as an assembly of a number of modules, each of which can be separately replaced. In order to represent functional connections between components in the graph, the user requirements in the project brief are also represented as nodes, and connected to the components that satisfy them.

Following this, building systems in the project's design, or parts of these systems, are ordered according to an initial assessment of their replacement rates. This assessment is based on the expected physical obsolescence rates of the components, and on typical maintenance policies and changes in use. Since the functional requirements in a specific project may cause the replacement rates to be different, the implications of different scenarios for future changes to the requirements are then identified and analyzed. The components that satisfy a requirement that could change in the future, and which will therefore be affected by this change, can be identified in the graph-based model using a path search algorithm that traces the links that connect the project requirements to the components (Figure 3). The replacement rates of the affected components are adjusted when changes are expected to occur sooner than the assessed replacement rate of the building system to which they belong.



a. Initial replacement rates of components

b. Adjustment of replacement rates

c. Clustering

Figure 3 – Design modularization using a graph-based model

Following the adjustment of the replacement rates of the components, groups of components with similar replacement rates can be identified using a graph clustering algorithm (Figure 3). These groups are represented by clusters of nodes in the graph that have the same attributes. Links between clusters of nodes in the graph represent dependencies between groups of building components with different replacement rates. A systematic reduction of these dependencies, through the design of modules with standard and flexible interfaces, may allow the building to be more easily adapted at some point in the future.

CONCLUSIONS

The proposed synthesis of BIM and graph theory is expected to facilitate the development of new tools for representing, managing and analyzing the design of building projects. A graph-based model of building projects contains a reduced amount of information relative to BIM, and is therefore likely to be more easily integrated and adjusted. It can also facilitate a graph-based analysis that may be useful to answer many questions regarding building projects, such as an assessment of the expected impact of proposed design changes, and of the optimal modularization of the design. The present research in the development of this model is currently focusing on developing tools for automatically translating BIM into graph-based representations, and for analyzing these representations using different algorithms.

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