MODELING CHANGE IMPACT FLOWS IN CONSTRUCTION PROJECTS

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ABSTRACT

In an ongoing research, a model of construction projects is being developed which can facilitate the analysis of the expected impact of proposed changes. The research examines the hypothesis that it is possible to conduct such an analysis before a change is implemented in the project, since much of the required information already exists when the change is proposed, though it currently remains largely inaccessible or difficult to obtain.

A number of graph-theoretic tools and algorithms are used in the model to analyze change impacts. A graph-based Project Connectivity Model represents the information required for providing a rough indication of the possible implications of a proposed change. A clustering algorithm and a path search algorithm are used to identify project elements which are likely to be affected by the change. The propagation of a change impact in the project is modeled as a Change Impact Flow. A quantitative assessment takes into account the ability of project elements to absorb a Change Impact Flow through buffers. This assessment can be highly uncertain. Hence, a non-probabilistic info-gap model is used to represent the uncertainty.

KEY WORDS

Construction management, Change management, Project modeling.

INTRODUCTION

Changes that are implemented in construction projects often have an impact which is difficult to predict and control (Lee and Pena-Mora 2007). This impact may eventually cause the project to deviate from client objectives such as the cost of the project, the date of completion and performance requirements.

The implementation of changes in construction projects is currently managed through change order management systems. These systems are based on the assumption that project managers can obtain information on all the expected implications of a proposed change before it is implemented, in order to allocate the appropriate resources to accommodate them. However, a number of researches have shown that project managers often face considerable challenges in obtaining such information (Cox et al. 1999; Hanna et al. 1999; Love et al. 2002).

In practice, a full understanding of the implications of a change is often achieved only after it has been implemented in the design and plan of the project (Hegazy et al. 2001; Motawa et al. 2007). The implementation of changes is a complex and iterative process, which may extend over a long period of time. It may include additional modifications which are made in order to accommodate the impact of the initial changes. After a change has been fully implemented, its actual impact may be quite different from the initial assessment. At that stage, it is obviously much more difficult

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to make adjustments. It is often too late to consider alternatives to the implemented changes without causing significant delays and cost increases.

Although change orders have not been addressed in detail in lean construction research, they have been mentioned as an important source of variability in construction projects (Vrijhoef and Koskela 1999). Variability has been recognized as being a major source of waste and loss of value in projects, in particular due to its impact on workflow reliability (Ballard and Howell 2003a; Koskela 1992; Tommelein et al. 1999). The reduction of variability is consequently seen as a basic principle of lean construction management, though it has been suggested that variability cannot be completely eliminated, and should be seen as a fact of engineering and construction life (Ballard 1999).

Lean construction research discusses two techniques through which variability can be accommodated: (a) the Last Planner system and (b) buffering. In the Last Planner system, decisions on the execution of planned tasks are delayed until the planner is confident that these tasks can be made ready when scheduled, and that their completion releases additional work that is requested by someone else (Ballard and Howell 2003b). Tasks can also be protected from upstream variability through the use of buffers, such as schedule buffers and plan buffers (Alves and Tommelein 2004). Schedule buffers (e.g. materials, equipment, manpower etc.) are placed between a variable task that produces or uses a resource and another task that requires that resource (Ballard and Howell 1995). Plan buffers consist of backlogs of work for crews that are used to ensure reliable workflows. To the best of our knowledge, buffers in the design and requirements of projects have not yet been directly addressed in lean construction research

Schedule buffers are considered a source of waste that should be minimized through better coordination and planning (Vrijhoef and Koskela 1999). Dependencies between tasks in the project often cause variability to have an indirect impact on downstream work. This has prompted researchers to define construction projects as closely coupled networks, which behave as complex adaptive systems (Bertelsen 2004; Bertelsen and Koskela 2003). These aspects of construction projects are also the focus of the present research.

RESEARCH OBJECTIVES AND MODEL REQUIREMENTS

This paper presents an ongoing research for the development of a model of construction projects, which facilitates the analysis of the expected impact of proposed changes. The analysis takes place prior to the implementation of the changes in the design and planning of the project. The present research examines the hypothesis that it is possible to conduct such an analysis, since much of the information that is required already exists when a change is proposed, but remains largely inaccessible or difficult to obtain. This information is currently dispersed among various databases, or exists as tacit knowledge, possessed by different project team members.

This research objective of facilitating the analysis of the change impacts is pursued by (a) automating the tasks required for the identification of those changes which may have a significant impact on the primary objectives of the client (cost, schedule and performance), and (b) enabling quick feedback for the project team.

Three basic requirements have been identified for the proposed model:

1. The model has to support the integration of various existing sources of information in the project in order to allow the analysis, in a single framework, of the impact of proposed changes on different aspects of the project.
2. The model has to be flexible enough so that it is easy to adapt and extend it to include changes. It should support the automatic propagation of change events, in order to relieve users from having to adjust the model manually.
3. The model has to represent the uncertainty that exists regarding the impact of changes prior to their implementation in the project.

Several efforts are being made to integrate different sub-models of construction projects (e.g. requirements, design, planning, risks, etc.). These include the integration of design and building codes (Eastman et al. 2009), and the integration of design and life-cycle costs (Kohler and Lutzkendorf 2002). Progress has been made in the integration of design, estimating and scheduling information (Hartmann et al. 2008). Central to these efforts is the definition of engineering data standards, such as Industry Foundation Classes (IFC) (IAI 2010). However, current tools still do not sufficiently support the integration of information that is produced and accessed simultaneously by many users (Halfawy and Froese 2005). Work routines vary from project to project, and even between different stages of a single project. The development of tools that can be adjusted to these work routines, and that can integrate the information produced in them, is proving difficult (Hartmann et al. 2009). The efforts to develop data standards may in fact be conflicting with the requirements to adjust information systems to local project routines.

Similar difficulties hinder the development of flexible and adaptive project models. While Building Information Modeling (BIM) tools allow certain adjustments to be carried out automatically through parametric techniques, these techniques are not being widely used in the AEC industry to integrate the work of multiple disciplines (Haymaker 2006). Instead, dependencies in the project data are often stored in the heads of practitioners, and the information is adjusted through time-consuming and error-prone processes.

Uncertainty is currently treated in construction projects through risk analysis and management tools. These tools are not integrated, and are based on two distinct methods, with different data sets: (a) risk registers and (b) stochastic cost and duration estimates. Risk registers tend to address only a small proportion of the many sources of uncertainty in a project (Ward and Chapman 2003). Moreover, dependencies between risks, which may occur when they have an impact on the same components or tasks, are often ignored, in spite of the fact that the risks may thus have an indirect impact on one another (Ackermann et al. 2007). Stochastic cost and duration estimates do not explicitly address the assumptions and conditions concerning the events upon which they depend (Ward and Chapman 2003). It is often not clear, for example, whether these events include the specific risks already identified and quantified in the risk register. Moreover, dependencies between the estimated probability distributions, caused by common risks, are ignored (Yang 2006). The proposed model should, therefore, link project elements explicitly both to identified sources of uncertainty, <u>and</u> to the assessed impact of that uncertainty on the client objectives. Thus, it could integrate information which is currently dispersed, due to the use of different methods of risk analysis.

A GRAPH-BASED APPROACH TO PROJECT MODELING

Current models of construction projects lack the ability to simultaneously integrate information from multiple domains. They also lack the flexibility to adjust to changes, and the ability to adequately represent uncertainty. Integrating all the project data in an easily adjustable model, while taking into account all possible uncertainty, is an extremely difficult (if not impossible) task. Instead, a graph-based approach is used in the present research to define a generic *Project Connectivity Model* (PCM), which represents only that information which is essential for providing a rough indication of the possible implications of a proposed change. Relevant and useful information is automatically extracted from the various documents and databases in which project data are stored, such as the building program, design, schedule and budget, and imported into a graph-based PCM. The reduced amount of information can be more easily integrated and updated. This information may not be sufficient for supporting the actual implementation of the proposed change in the design and planning of the project, but it can provide an indication of the impact of the change on the client objectives.

Graph theory contains a wealth of tools and algorithms, whose possible use in project management has remained largely unexplored. A number of these are used in the PCM, in five different stages, to analyze the implications of a proposed change:

1. A graph is used to represent the project elements and their relationships
2. *Graph transformations* are used to adjust the model to changes
3. A *clustering algorithm* is used to identify critical relationships that propagate the impact of the change
4. A *path search algorithm* is used to identify and trace specific change impact flow paths
5. A *network flow model* is used to quantitatively assess the impact of a proposed change

PROJECT CONNECTIVITY MODEL (PCM)

The PCM is a generic graph that stores information on various elements in the project, such as requirements, components, tasks and resources, as well as on the relationships that exist between these elements. The elements are represented as nodes in the graph, and the relationships as arcs linking the nodes (

Figure 1). A relationship between project elements indicates that a change to one element may result in a change to the other. The model thus supports a hierarchic and schematic representation of the project, lacking in current BIM tools which support only the obvious 2D and 3D graphic representations (Boeykens and Neuckermans 2008). The model integrates information concerning different aspects of the project, such as the client requirements, building program, design and planned tasks. These are represented as distinct layers in the PCM. The model incorporates new data, which is produced by different members of the project team as the project evolves. At each stage of the project a new layer is defined in the model. The new elements in the additional layer are connected to the elements in existing layers, as well as to the client objectives concerning the project's cost, schedule and performance.

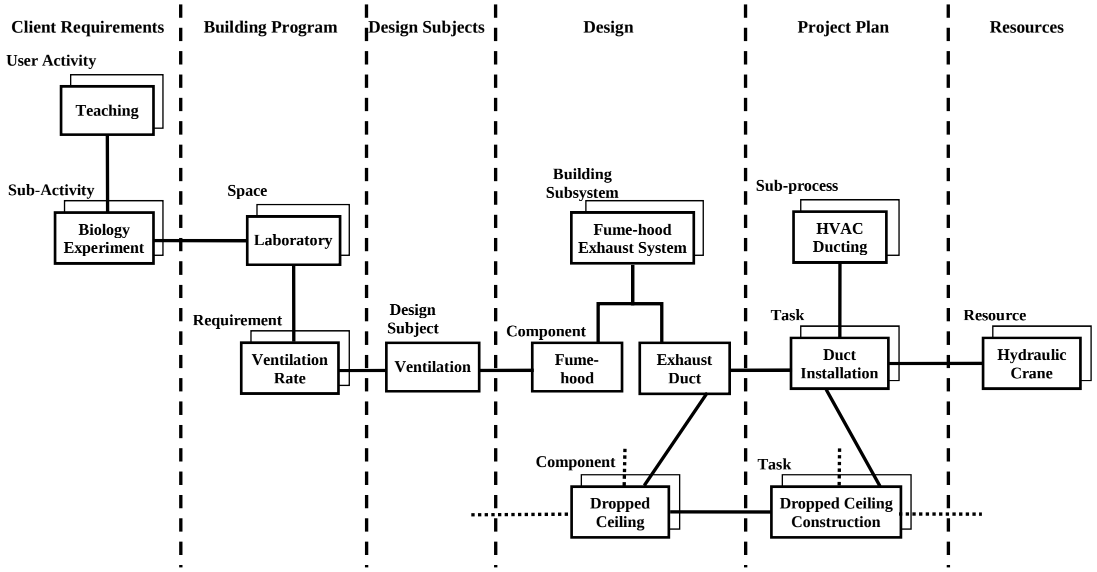

Figure 1: Elements and relationships in the Project Connectivity Model

Project data is decomposed, within each layer, into subsystems such as building subsystems in the design, and sub-processes or sequences of tasks in the project plan. A distinction is accordingly made between different types of relationships in the model:

- Relationships within a subsystem – such as those linking a planned task to the sub-process to which it belongs, or those linking a requirement in the building program to the space for which it has been specified. These relationships are directed and hierarchical, and can be represented with trees (i.e. connected acyclic graphs). The relationships are predefined and long-term in the sense that the "child" in the tree does not exist without its "parent". They are usually defined by a single designer or planner in an appropriate sub-model, and are therefore more easily identified.
- Relationships between aspects of the project (or across layers of the model) – such as those linking a building component in the design to the requirement in the building program which it may satisfy, or those linking a building component to the planned task of its construction. These are undirected, non-hierarchical relationships, and can be represented with networks. They are more dynamic and transitory, in the sense that each one of the elements has its own lifecycle, and can be created and deleted independently. They are usually the product of collective teamwork and often not documented in an integrated model. They are therefore less easily identified.
- Non-hierarchical relationships within the same aspects of the project – such as those linking two subsystems in the design which are physically connected, or those linking adjacent spaces in the building program. These relationships are also relatively dynamic and transitory, since they depend on the adjacency requirements in the building program, the physical design, and the resource allocation in the project plan.

GRAPH TRANSFORMATIONS

Changes are automatically implemented in the PCM through the use of generic, predefined rules called Graph Transformations (Heckel 2006). Such changes may involve adding a new element to the PCM, deleting an existing element, and merging or dividing existing elements. By using Graph Transformations, the project team is notified of the need to make the necessary adjustments to the model. When, for example, an element is added to the model, new relationships with other existing elements in the model must be defined, while maintaining the correctness and consistency of the model. Predefined types of relationships specify which elements can be linked.

CLUSTERING ALGORITHM

A change to an element in the project may have a direct impact on other elements in the same subsystem, to which the changed element is directly linked. The change may also have an indirect impact on elements which belong to other subsystems in the project. The indirect impact is propagated through non-hierarchical relationships which link subsystems within the same aspect of the project. Such critical relationships may increase deviations from client objectives by propagating the change impact to other areas in the project. These critical relationships may exist between any two elements – spaces in the building program, components the design, or tasks in the schedule. They are automatically identified using a divisive global graph clustering algorithm. Divisive clustering algorithms are a class of hierarchical methods that work top-down, recursively partitioning the graph into clusters. Previous research has examined the use of clustering algorithms such as Matrix-based clustering (Browning 2001) and Spectral clustering (Smith and Eppinger 1997) in project management. The present research, however, examines the application of graph-theoretic approaches such as Minimum-cut clustering (Hartuv and Shamir 2000) and the Girvan-Newman method (Newman and Girvan 2004). These graph-theoretic algorithms are more suitable for the Project Connectivity Model, which on the one hand lacks detailed quantitative information, but on the other hand includes complex clusters which tend to overlap.

PATH SEARCH ALGORITHM

Clustering can be used within a layer of the model, which represents a specific aspect of the project. However, inter-layer relationships usually make it impossible to divide the entire project into distinct clusters. After applying the clustering algorithm, the next stage of the analysis uses a depth-first path search algorithm to further reduce the search space. In order to identify specific project elements which are likely to be affected by the change, the relationships through which the change impact may propagate are identified, one after the other, in the PCM, until a client objective is reached. This can be done automatically since the affected elements are all linked, directly or indirectly, to the element on which the initial change was performed. The path search algorithm identifies different paths that lead from the changed element to different client objectives. For example, when a change is proposed for a window in the design, this change may have an impact on both the performance and cost objectives (Figure 2). The propagation of the change impact is traced through a relationship of the window component with a requirement for a specified level of illumination. The propagation path is further traced through an indirect relationship of the requirement with a planned user activity, and ultimately to the performance objective. A different path is traced from the window component to the resources required for its supply, and ultimately to the cost objective. Additional paths, not shown here, are identified as well.

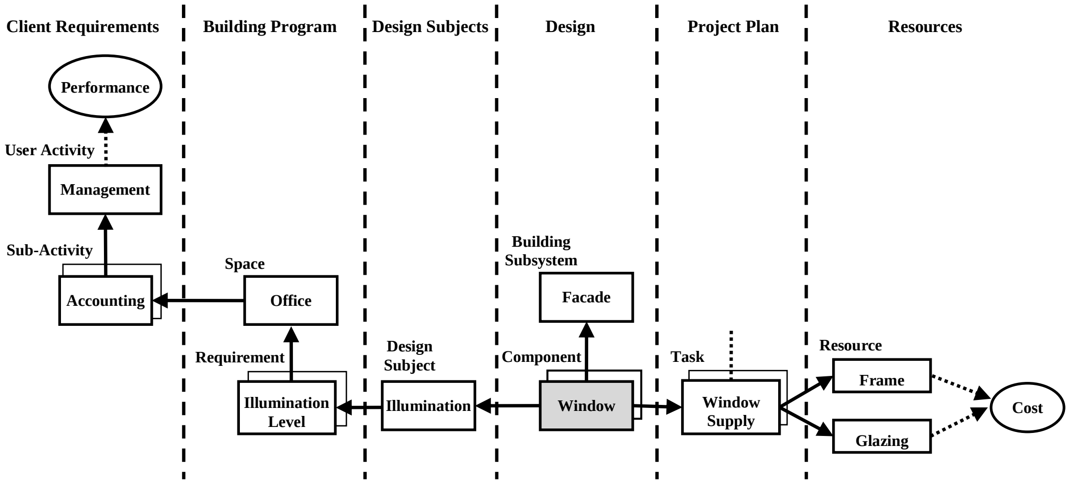

Figure 2: Tracing CIF paths that lead to different client objectives

Many indirect implications (or "knock-on effects") of changes in construction projects are the result of additional actions taken by project management, to cope with the direct implications of the original changes. The direct implications may create a situation in which the modified project is inconsistent with the client objectives. The project team may then decide to take action and make additional changes in order to realign the project with its original goals. However, these changes may have their own consequences, which are often difficult to identify. For example, the Project Connectivity Model can show that the change to the window component will create a situation in which the required illumination is no longer provided. The project team may decide to correct this deviation from the performance objective by adding lighting fixtures in the design (Figure 3). However, redesigning the lighting fixtures may require further changes to other building subsystems integrated in the dropped ceiling, leading to unforeseen delays in the schedule. Thus, the PCM allows the project team to define a decision on an additional change, and analyze its implications.

Once the Path Search algorithm has identified all the paths that lead from the changed element to client objectives, a sub-graph is created, containing only the elements on the paths that have been identified. This sub-graph is then used for a quantitative analysis of the impact of the proposed change. The propagation of change impacts in the project is modeled as a *Change Impact Flow* (CIF). The change impact flows from the project element on which the initial change was performed to other, directly or indirectly affected, elements. The size of the CIF which reaches other elements reflects the degree to which they are expected to change as a result of the impact of the initial change.

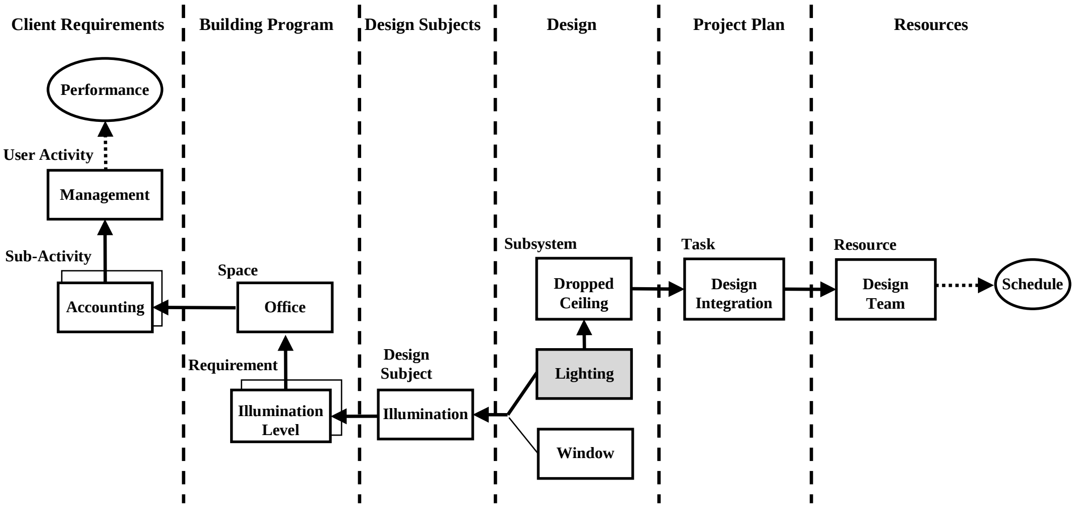

Figure 3: Tracing the propagation path of a change that is implemented to cope with the implications of a previous change

A quantitative analysis must take into account the diversity of relationships in a project, which can be strong or weak, and may suppress or increase the CIF. The definition of coefficients for the relationships makes it possible to use methods which have been developed for network flow models. In such models, nodes (i.e. project elements) are connected to a source where the initial event (i.e. change) takes place and every node is assigned a sink where the flows are directed to. The ability of a project element to absorb a CIF depends on the buffers that were included in its definition. Buffers are therefore a means to reduce dependencies, and can prevent the CIFs from reaching certain project elements. In the PCM, the sink represents a buffer which is included in the project element, and can absorb part of the CIF. When flows reach a node, they may be absorbed by the sink or, if they are large enough, flow further through the network via relationships, eventually reaching the ultimate sink (i.e. client objective).

The proposed model requires an assessment of coefficients for the relationships between the project elements, specifying how much of the change impact flows through these relationships. These assessments can be highly uncertain, and the present research uses a non-probabilistic info-gap model to represent this uncertainty. An info-gap robustness function in the model outputs the greatest amount of error, in the assessed coefficients, that can be tolerated without the proposed change causing a deviation from the client objectives. Thus, an assessment is made of the vulnerability of the client objectives to a proposed change in the project.

CONCLUSIONS

Typically, a large number of changes will be made during the lifecycle of a construction project. As we move further away from a changed element, buffers that exist in the project (because it is not optimal and contains tolerance margins) usually make it possible to absorb CIFs. Most of these changes will therefore affect only a limited number of project elements, without having a significant impact on the client objectives. A small number of changes will, however, have an impact that propagates dramatically and reaches the client objectives. The PCM provides tools to predict the propagation of the change impact from an element to the client objectives, and identify proposed changes that may cause deviations from those objectives. The model also allows the project team to evaluate possible actions it might consider in order to accommodate the identified implications of a proposed change. Further changes may have to be made to compensate for the deviation, or the client objective may have to be changed.

In order to fully predict CIFs, it is essential to understand the current state of the buffers for each project element – buffers in the building program and design, as well as in the project plan. A construction project evolves throughout the project duration, during which the characteristics of the project, such as precedence relationships and resource constraints, continuously change. An analysis of the available buffers in a project needs to consider these changing conditions. CIFs can be controlled by explicitly creating and managing buffers. However, in order to be effective and efficient, these buffers have to be continuously updated, based on the information obtained from the project team.

Unplanned changes can also be seen as an opportunity to analyze the efficiency of the proposed design and plan, by revealing previously hidden buffers. Ballard (2008) has noted that, though buffers can be an important tool to absorb variability in a project, they often exceed what is needed for this purpose. The PCM can be used to reveal the buffers that currently exist in the project definition, but remain hidden and unused. The use of the buffers to absorb CIFs can be examined, and the buffers can be matched to the actual variability in the project.

The ongoing development and validation of the PCM is being carried out through its implementation in case-studies of construction projects. Several pilot studies have been carried out so far, yielding promising results. In these studies, the PCM took into account information which had existed when the changes were proposed, but had not been used by the project teams. An analysis could be conducted which, though approximate, provided valuable information on the possible implications of changes. The implications which were identified in these studies matched the actual consequences of changes that were observed. They also included implications that were not identified by the project management when these changes were proposed in the case-study. These results support the hypothesis, that it is possible to conduct an analysis of the impact of a proposed change before its implementation in the project.

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