A GRAPH-BASED APPROACH TO THE MODELING OF CHANGES IN CONSTRUCTION PROJECTS

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ABSTRACT: The implementation of changes in construction projects often causes deviations from the objectives of the project client. One of the causes of this problem is that the tools currently used in projects do not support the identification of the consequences of a change before it is implemented in the project. The objective of the present research is to develop a model which facilitates an automatic identification of proposed changes which may have a significant impact on the objectives of the project client. The present research adopts a graph-based approach to the modeling of construction projects. A graph-based model was found to provide a simple but informative representation of the structure of projects, which can facilitate an 'order of magnitude' approximation of the impact of proposed changes. Graph theory provides a wealth of concepts, tools and algorithms, which were used in the present research for an analysis of the impact of proposed changes.

Keywords: *Change Control, Project Modeling, Project Management, Decision Making*

1. INTRODUCTION

Automated Data Collection technologies currently make it possible to track the location of workers, materials and equipment in construction projects, and to record in real-time the actual state of the project. Various models have been developed that automatically transform this data into useful information, in order to support real-time control of construction projects [10]. These models identify deviations of the actual performance on the construction site from the desired performance. The project team can then implement necessary changes or adjustments to the project, in light of these deviations.

However, the complexity of construction projects and the interactions between project elements make it difficult to know a priori how changes in specific project elements, implemented in order to resolve an existing deviation, will affect the entire project [4,9]. Such changes and their impacts may eventually cause the project to deviate even further from client's objectives. In practice, it is currently necessary to implement changes in the physical design, planning and actual construction of projects in order to achieve an understanding of all their implications [5,8]. The implementation of changes is often a lengthy and iterative process, and once the full extent of their impact becomes clear, it is often too late to make adjustments in order to realize the original objectives. It may be too late to consider alternatives to the implemented change, without causing significant delays and cost increases.

In the present research, a model for look-ahead control of construction projects has been developed. The model facilitates the assessment of the possible impact of changes when they are initially proposed, and prior to their implementation in the project. Changes which may eventually cause significant deviations from the client's objectives can thus be identified. The model deals with proposed changes in the requirements and design of the project, in addition to changes in the project plan.

2. THE PROJECT CONNECTIVITY MODEL

The present research uses a graph-based model of construction projects that obtains its input from existing databases in the project, such as the building program, design and schedule. Since the proposed model focuses on the relationships which connect different project elements, it is called a Project Connectivity Model. Different aspects of the project are represented as layers in the Project Connectivity Model. The project elements (e.g. requirements, components, tasks and resources) are represented as nodes in a graph, and different types of relationships linking these elements are represented as arcs between the nodes.

The graph-based representation facilitates the integration of project information. For example, the requirements in the building program and the building components in the design are linked through objects call Design Subjects, which are represented as nodes in the graph [6]. A Design Object defines which components may satisfy a specific requirement, and vice-versa.

New elements can be automatically incorporated in the Project Connectivity Model, and existing elements can be automatically adjusted according to proposed changes, through the application of Graph Transformation (GT) rules. GT is a technique for implementing changes in graphs through an automatic application of predefined rules [3]. GT can be applied to the relationships between elements (or nodes) in the model, as well as to the attributes of the elements. The GT rules specify how the model should be built, and how it can evolve [7].

Once the information regarding the project has been integrated and updated, the model facilitates two types of analysis to determine the eventual impact of a specific change:

- A qualitative, static analysis of the topology of the network of project elements, using graph-theoretic algorithms. The model identifies the elements that are likely to be affected by the change, based on their connectivity.
- A quantitative, dynamic analysis of the propagation of the impact of the change. The impact is modeled as a flow in the network of project elements, in order to assess the resulting deviation from the client's objectives. Uncertainty is incorporated through non-probabilistic methods.

3. ANALYZING THE TOPOLOGY OF THE NETWORK OF PROJECT ELEMENTS

Construction projects consist of complex networks of interrelated elements. The relationships between components that belong to a specific subsystem in the design, (such as a structural or mechanical subsystem) may cause a change in one component to have an indirect impact on other components. Similarly, the relationships between construction activities that belong to a specific process in the plan (such as the construction or installation of a component) may cause a change in one activity to have an indirect impact on other activities. Such impacts often lead to incremental deviations from the client's objectives in a project, such as the facility's cost, date of completion and conformance to performance requirements. An identification of such subsystems or processes, which consist of strongly connected project elements, can facilitate the assessment of the possible impact of changes prior to their implementation. This in turn could reduce deviations from the client's objectives.

Additional relationships may, however, also link elements which belong to different subsystems in the project's design or plan. Two components, which belong to different subsystems in the design, may be physically connected. This may cause a change in a mechanical component, for example, to have an impact on a structural component. Similarly, two activities, belonging to different processes in the plan, may be related because they use the same resource.

Overall, the relationships linking elements within a subsystem or process are more numerous that those linking elements belonging to different subsystems. It would be a mistake, however, to ignore the relationships between subsystems. Such relationships can be critical, as they may propagate the impact of a change to additional subsystems in the projects, leading to increased deviations from the client's objectives. Moreover, these relationships are often overlooked by project teams. While relationships between elements within a subsystem or process are generally well documented, project team members may not be aware of relationships that link elements belonging to different domains, and which do not fall under the responsibility of a specific consultant or sub-contractor.

The graph-based representation of project elements and their relationships allows the implementation of clustering algorithms in order to automatically identify clusters of closely connected elements, as well as the relationships linking the clusters. This in turn can facilitate the identification of the possible impact of a proposed change in one project element on other elements in the same subsystem. It also allows the project team to assess whether the decoupling of certain critical relationships, which link this subsystem to other subsystems in the project, might prevent deviations from the client's objectives.

Different types of clustering algorithms were tested in the present research. Two clustering algorithms that were tested but did not give good results were based on the use of a Design Structure Matrix, and on an analysis of the eigenvectors of the adjacency matrix representing the graph [11,13]. Both types of algorithms were not suitable for identifying clusters in graphs representing construction projects, which exhibit complex structures of overlapping and nested clusters.

Good results were obtained using hierarchical clustering algorithms, which assume that a graph can be defined as a hierarchical structure, where each top-level cluster is composed of sub-clusters and so forth [12]. Unlike the other methods, the hierarchical clustering method could be used to identify clusters even when they overlapped, or when they were nested within larger clusters. Case studies of construction projects that were modeled in the present research, and used to test the clustering algorithms, always reflected a hierarchical structure of several layers of clusters. The results of applying the clustering method were especially interesting when the clusters that were identified differed from the existing “official” hierarchy, such as the hierarchy defined the by the division of responsibility between different engineering disciplines or contractors.

When the clustering algorithm was applied in a model that included several aspects of a project at once (e.g. the project's requirements, as well as its design and planning), results were poor. In such cases, the clustering algorithm was generally not able to decompose the graphs into distinct clusters at all. However, changes that are made in construction projects often have an unexpected indirect impact on multiple aspects of the project. A delay in a planned activity, for example, may have an impact on the allocation of resources, and thus indirectly affect other activities which use the same resources (e.g. workspace, equipment, manpower, etc.). This may eventually lead to deviations from the budget or schedule of the project. Similarly, a change in the design of a component may have an impact on the performance of the facility, and thus indirectly affect other components which satisfy the same performance requirement (e.g. thermal comfort, air quality, acoustics, etc.). This may eventually lead to deviations from the project's planned performance or cost. Such indirect impacts and the resultant deviations are often not correctly predicted.

In order to facilitate an identification of the possible impact of a change on different aspects of the project, and ultimately on the client objectives, path search algorithms were used. The path search algorithms trace paths of relationships through which the impact of a change may propagate, from the element for which the initial change is proposed, to the client objectives. Thus, the elements which may be affected are identified, as is the possible impact on the client objectives. The model identifies in a similar way the impact of additional changes, which the project team may consider implementing in order to cope with the deviations caused by the initial change.

The application of the clustering and path-search algorithms can give the project team a rough impression of the possible range of the impact of a proposed change. It is obviously not sufficient for the actual implementation of changes in the design and plan, but it does allow the project team to identify a cluster of components in the design, or tasks in the schedule, which are likely to be affected by a change to an element in the same cluster. Since the clustering algorithm decomposes the project in ways which may differ from existing definitions of the project, it may help the team to differentiate between clusters of interconnected elements, of which the team may not have been aware. The model also allows the team to use path-search algorithms to identify critical relationships which link elements in different aspects of the project. Such relationships are critical in the sense that they may indirectly cause deviations from the client objectives.

4. ANALYZING THE PROPAGATION OF THE IMPACT OF CHANGES

In order to facilitate an assessment of the magnitude of the impact of the change on the client objectives, the propagation of the impact through the network of project elements is modeled as a Change Impact Flow. The flow of the impact of a change is defined by the topology of the network of project elements. The impact may, for example, flow simultaneously on parallel links in the network, reaching additional elements in the project.

The size of the deviations, caused by the indirect impact of a change, depends on the use of buffers located on the paths that link the element which was changed with the client objectives. These buffers may absorb a fraction of the Change Impact Flow. Some buffers, such as contingencies in the budget and time buffers in the schedule, can be automatically identified. Other buffers, such as tolerance margins that are incorporated in the design of components, may not be documented and are difficult to identify automatically. While discussion on the use of buffers in project plans has been extensive, in particular regarding time buffers, the use of buffers in the requirements and design of construction projects has been largely ignored in construction management research. This is surprising, since the role these buffers fill in the management of changes in projects is probably as important as that of buffers in the project plan.

The model can be used to reveal buffers that exist in the project, but remain hidden and unused. The use of the buffers to absorb the impact of changes can be examined, and the buffers can be matched to the actual variation in the project. The model may also reveal the fact that the existing buffers in a project are not sufficient to absorb the impact of a change. It is then a managerial decision whether or not the proposed change should be implemented, given its consequences, and if so, how these consequences should be dealt with.

The model allows the project team to identify which type of change impact propagation process can be expected to occur if a proposed change is implemented. Change impact propagation processes can vary from an impact that is restricted to the element to which the change is applied, to an impact on a larger part of the project which is eventually absorbed by buffers, and up to a large impact on different client objectives which is difficult to control.

However, when a change is initially proposed, and prior to its implementation in the project, there is considerable uncertainty regarding the assessment of its impact. This uncertainty had to be incorporated in the model that was developed in the present research. Currently, uncertainty in construction projects is often treated through risk analysis and management tools. These tools, however, are not integrated. They do not link project elements both to identified sources of uncertainty, and to the implications of this uncertainty on the end result. This makes it difficult to update the risk assessment according to changes in the project, and leads to dependencies between risks being ignored.

An additional drawback of existing risk analysis and management tools is that they are based on probabilistic methods. In general, these methods can be applied using statistical data to forecast an uncertain future. In construction projects, however, statistical data of similar changes which were implemented in the past is usually not available, because it is not systematically collected [14]. Therefore, one would have to rely instead on probabilities assessed by team members, based on their experience and tacit knowledge. Such assessments may, however, be inaccurate due to a lack of knowledge in probability theory, which makes it difficult for team members to translate past experience into probabilities [2]. Moreover, construction projects are complex and unique. Many interconnected factors have to be taken into account, and no previous projects are identical (or even highly similar). This makes it difficult to define which previous cases are similar to a proposed change in a construction project.

In the present research, two alternative approaches to probabilistic methods are explored. One approach is the systematic use of scenarios. Instead of asking the project team members to identify possible "risks" in the implementation of the proposed change, and assess their impact, they are requested initially to define a desired outcome, or aspiration level. The size of the impact of the change on the client objective is adjusted in the model so that it matches an outcome which is deemed unacceptable in light of the client objectives. The propagation path of the impact of the change, which has already been identified using the model, is then traced in the opposite direction, from the client objective back to the project element for which the change is proposed. Tracing the path backwards, the buffers and sensitivities in each relationship are reassessed. The analysis allows the project team to assess whether an unacceptable deviation is likely or not to occur as a result of the proposed change.

An alternative approach to the use of scenarios that was tested in the present research was the use of a non-probabilistic info-gap model of uncertainty. Info-gap decision theory adopts a robust-satisficing approach to uncertainty, seeking a decision which satisfices the performance and is robust to uncertainty [1]. This is done by identifying a decision that maximizes the size of errors that can be tolerated in the nominal estimates, while guaranteeing a specified critical level of performance.

Simulations that were carried out indicate that the scenario-based approach allows experts to take into account information that is otherwise ignored. The method, in which experts are asked to identify possible alternative scenarios for deviations from the client objectives, highlights those aspects of a change that are risky and should be carefully managed and controlled. The ability to implement the proposed info-gap model in case-studies was restricted, however, due to the fact that existing buffers in construction projects are currently often not documented. In addition, experts found it difficult to quantify the sensitivity of project elements to changes. A solution to this would be a more systematic documentation of buffers in construction projects – not only in the project plan, but also in the requirements and design of a project. Additional research can also lead to a better understanding of the quantitative relationships between different project elements.

5. CONCLUSIONS

The present research adopts a graph-based approach to the modeling of construction projects. A graph-based model was found to provide a simple but informative representation of the structure of projects, which can facilitate an "order of magnitude" approximation of the impact of proposed changes. The model represents only a fraction of the original information that exists in the different sources from which its input is obtained. Such a reduced amount of information can, however, be more easily integrated and adjusted. Moreover, graph theory provides a wealth of concepts, tools and algorithms, such as graph transformations, clustering algorithms, path search algorithms and network flows. The results of tests in which the model was implemented indicate the advantages of applying such tools in construction project management. They were used in the present research for a stepwise analysis of the impact of proposed changes. This analysis consists of a series of steps which gradually narrow down the search space, and focus more and more on those elements that are likely to be affected by the proposed change.

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