Feasibility Study of an Automated Tool for Identifying the Implications of Changes in Construction Projects

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Abstract: Because of the fragmented nature of project information, decisions on changes in construction projects are usually based on project design instead of project requirements. This research proposes a new approach for coping with changes in construction projects: A change control tool (CCT) that will identify implications of a change as soon as it is proposed. The tool will ensure that the stakeholders involved in the decision process in which change proposals are evaluated will know in advance if a change could cause the project to stray from its original goals, as expressed in the requirements. The proposed CCT uses the building program as a link between client requirements and the building design and traces the different relationships that exist between the requirements in the project. The relationships are traced using requirement traceability capabilities on the level of a specific space in the project and on the level of the entire project. A preliminary CCT model was developed and pilot studies implementing the model have been conducted. The pilot studies have given positive results, indicating that the CCT could identify the scope of the proposed changes' implications.

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Introduction

Change orders are considered a major cause of project delay and are a source of many disputes in today's construction industry. The primary causes of change orders are owner-initiated changes and designer's errors and omissions (Love and Li 2000; Manavazhi and Xunzhi 2001). Changes occur during the course of many construction projects, and as a result, projects are often designed and executed in an iterative manner (Othman et al. 2004).

Construction projects are, however, often described in literature as linear processes: At their inception, requirements are gathered. These serve to define the spaces in the building program. The building programs in turn are used in the preliminary design. Later on, changes in design are based on previous design solutions. Eventually, construction planning is based on a final design.

In practice, construction projects are iterative, and their development is rarely strictly linear. For example, design solutions may raise new questions, causing changes in requirements late in the process. This will have a widespread impact on other requirements already specified (Barrett et al. 1999). It is common practice, however, to base changes in design on the current project design rather than on requirements documented in the building program. The disruption caused by changes is thus exacerbated by the fact that, when a change is initiated to satisfy a certain requirement in the project, its impact on other requirements is usually not considered. These impacts are often revealed only later in a project, when further changes are necessary to compensate (Lee et al. 2006). As a result, projects can stray from their original goals as expressed in the requirements, without the stakeholders making a conscious decision to do so.

The difficulty in identifying all the requirements that will be influenced by a proposed change arises from the fact that project design and management tools do not allow such identification. Traditional tools do not communicate relationships within project information (Liston et al. 2000) and do not support the documentation of requirement changes (Kiviniemi et al. 2004). As a result, the information produced in construction projects is fragmented and inconsistent (Russel and Froese 1997).

In projects involving large teams, it is impossible for every team member to participate in every project review, and the answers to questions concerning proposed changes are usually delayed, while the project is in progress. Often, changes are already implemented in the project before their full impact is understood, as a result of an optimistic bias concerning the changes' consequences and a desire to prevent project delay (Her Majesty's Treasury 1997).

It is clear that a need for efficient methods of information processing exists in construction projects. Such methods would facilitate effective data communication between various groups and levels involved in a project (Lo et al. 2006). In recent years, the use of building product models has become widespread (Ibrahim and Krawczyk 2003). This trend could allow the development of a tool that will link the different requirement sources and indicate the relationships between the requirements. Such a tool could automatically identify the impact of a proposed change of a certain requirement on the other project requirements.

Previous research efforts concerning changes in construction projects have focused mainly on two different approaches: The

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first approach was to seek methods to reduce the number of changes in a project by solving the problems that caused these changes, for example, by improving the client requirements capturing process (Kamara et al. 2000). The second approach was to seek methods to improve preparedness for unanticipated changes, for example, by using and maintaining buffers (Lee et al. 2006). This research proposes a new approach: To develop a tool that will identify the scope of a change's implications as soon as it is proposed to ensure that the stakeholders involved in the decision process in which change proposals are evaluated will know in advance if a change could cause the project to stray from its original goals.

Previous Related Work

Several previous research efforts have focused on automating the requirements definition process. In these solutions, the process of defining the requirements was restricted to a distinct phase at the beginning of a project, and the requirements were considered as an input to the design process, not to be changed by it. It has been noted elsewhere, however, that in many cases the requirements continue to evolve throughout the project life cycle (Othman et al. 2004).

In one such study, a Microsoft Access–based database application for client requirement processing was developed, using quality function deployment as its core technique (Kamara et al. 2000). It aimed to prioritize requirements and to manage the interests of multiple stakeholders in order to improve the client requirements capturing process. Another solution enabled activity-based cost management and included computer-aided applications for practical work (Pennanen et al. 2005). Client requirements such as user functions, geometrical and temporal needs, spatial performance, and associated costs were measured, and the required spaces in the planned building were defined accordingly.

Other previous research efforts focused on linking the requirements for a construction project to the design solution. These solutions were aimed at aiding designers in their work by making project requirements more accessible to users of CAD tools. In the present research, in contrast, change management is considered a group decision process, in which not only the designers but also other stakeholders such as the client, project-manager, and contractor take part. Client requirement capturing is not in the scope of previous research efforts, and the client needs from which the project requirements are derived are not included. It is therefore not possible, in these solutions, to consider the needs and wishes expressed by the client while evaluating changes in the project requirements.

In one study, a requirements model specification was created to enable active connections to the architectural design model (Kiviniemi et al. 2004). The model included both direct requirements for spaces and indirect requirements for the bounding elements and technical systems of these spaces. Another study uses requirement traceability to assist designers participating in collaborative design (Ozkaya and Akin 2005). In this study a process was described in which requirements and designs interacted continuously and requirements were created and modified as the design progressed. Designers built the relationships between the requirements, allowing other design participants to recognize implicit design information and use it for decision making.

Research Objectives and Assumptions

The objective of the present research is to assess the feasibility of a change control tool (CCT) that supports the decision process in which change proposals are evaluated, during the design and construction phases of projects.

The CCT is based on the proposition that the building program can serve as a framework for information management, with links to the client requirements and the building design. The CCT is expected to indicate the scope of a proposed change's implications by tracing the relationships between different requirements. The building program is a convenient framework for the CCT, as it represents the information in a format that is comprehensible to all project stakeholders. While clients may not always be skilled in reading building plans, other stakeholders may find it difficult to interpret the client requirements. Furthermore, as the information in the client requirements and the building design relates to different aspects of the project, it can be linked only indirectly, through the building program, which relates to both kinds of aspects. Thus, the building program can create a common language for the different stakeholders and link the different information sources. By allowing uninterrupted data exchange between the sources of information, the building program can be modified and kept up-to-date.

The CCT will be used in an integrated computer system for construction management that supports the exchange of information between various applications (Froese et al. 1997). This is, however, not in the scope of this stage of the research.

The research assumes that

1. To evaluate changes in the project requirements, the client requirements from which they are derived must be considered. The client requirements reflect the client's needs and wishes. The project requirements are the product of a process in which client requirements, together with requirements obtained from other sources, such as building codes and the project team's knowledge, are translated into design attributes that aid designers in their work. Therefore, the client requirements, captured by interviewing the clients and end-users of the building, are documented and updated.
2. Construction project requirements are usually recorded in a building program, which relates requirements to spaces in the project. The CCT is therefore based on the format of a building program.
3. The exchange of information between the building program and the building design depends upon the existence of an object-oriented model of the design solution, such as in Froese et al. (1998). Such a modeling tool allows the capture and management of information about the building design.

Principles of the Proposed Solution

The CCT is a decision support model that aids the process in which change proposals are evaluated. The building program serves as a framework for the CCT, with links to the client requirements and the building design. These three sources of requirements (client requirements, program, and design) differ in the way in which they are defined and documented and are each based on a different abstraction of the project (Fig. 1).

- The client requirements are analyzed in the CCT using an activity-based approach (Pennanen et al. 2005). They specify user activities that realize the client's goals and are therefore value-adding (e.g., teaching, research, administrative activities). This ensures that the requirements are systematically

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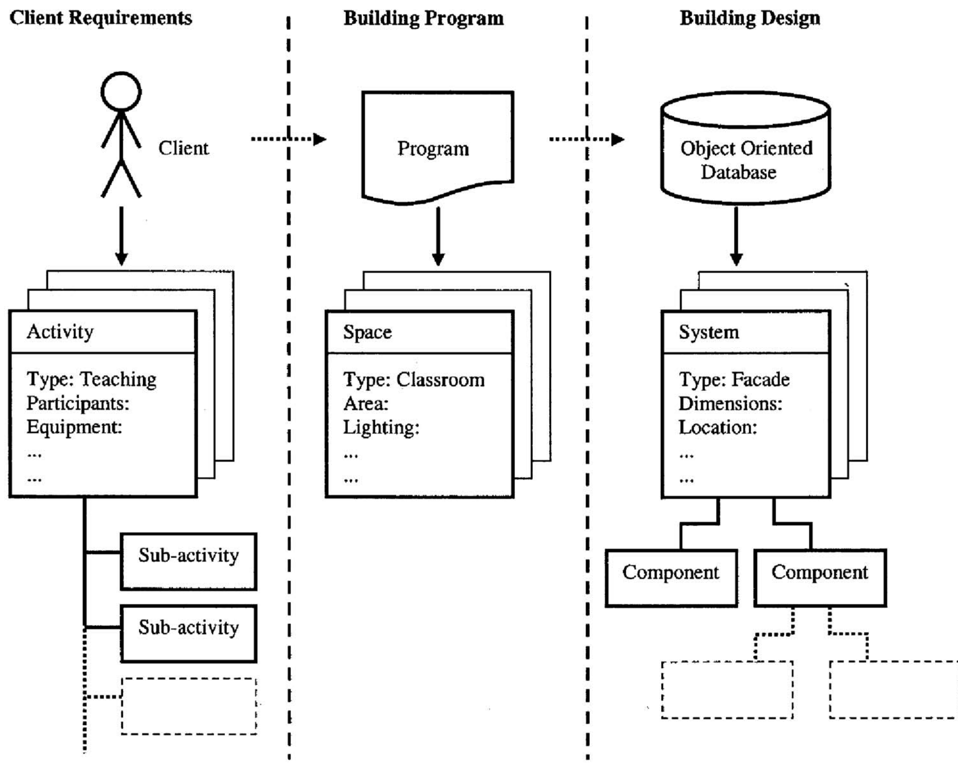

Fig. 1. Sources of requirements in building projects

mapped and are defined in a structured form. Client requirements are translated into project requirements, which are documented in the building program.

- The building program divides the planned project into spaces (e.g., classroom, lab, offices) and presents the project requirements for each space. These requirements aid designers in their work.
- The building design divides the project into discrete building systems: structure, plumbing, HVAC, electrical, etc. Each system consists of a large number of components designed to connect in a particular way. Each component is designed according to the project requirements, specified in the building program, of the space in which it is located.

The CCT is designed to identify the scope of the implications of a proposed change by using requirements traceability capabilities. It traces the different relationships that exist between the requirements. This is done on two levels: (1) a specific space and (2) the entire project.

Implications of a Proposed Change on a Specific Space

The links between the requirements in the different sources make it possible to identify the implications of a proposed change in one object (user activity, project requirement, or component) on other objects already specified for the same space. The link between project requirements and user activities is achieved by identifying the space to which they are related. The link between project requirements and design involves, however, a significant structural misalignment, which must be taken into account. The concerns identified in the project requirements, which are based on the project's features, are different from those used to modularize the design, which are the building systems and components of the project. These different structures mean that traceability between project requirements and design is normally poor.

Moreover, *scattering and tangling* may occur. A single project requirement can be satisfied in the design by many building components (scattering), and a component can contribute toward implementing many project requirements (tangling). For example, a project requirement for illumination may be satisfied by both windows and electrical fixtures, and a window may contribute toward implementing a project requirement for illumination, as well as a project requirement for ventilation. When the planned project is divided into spaces, a building program is produced that usually aligns well with the client requirements. As a result, however, the program may align poorly with the building design, thus introducing traceability problems.

It is proposed here to address the misalignment of project requirements and design with an approach called subject-oriented design, after a similar approach that has been introduced in the design of software systems (Clarke et al. 1999). In subject-oriented design, the design model is divided into design subjects (e.g., lighting and ventilation) and each design subject contains the components that satisfy a specific project requirement. For example, lighting design subjects will contain windows and electrical fixtures to satisfy the requirement for minimum illumination levels in a certain space (Fig. 2).

Design subjects can cut across building systems by containing components from different systems, and they can also overlap, as when two different subjects contain corresponding components. In the CCT, design subjects link built components with specific project requirements in the space in which they are located. Thus, when a change is introduced in a component or requirement, contradictions with other existing components or requirements can be identified. For example, when changing the size of a window to meet a requirement for illumination, the user will be warned that this could affect certain electrical fixtures, which also facilitate this requirement. In addition it will impact the requirement for

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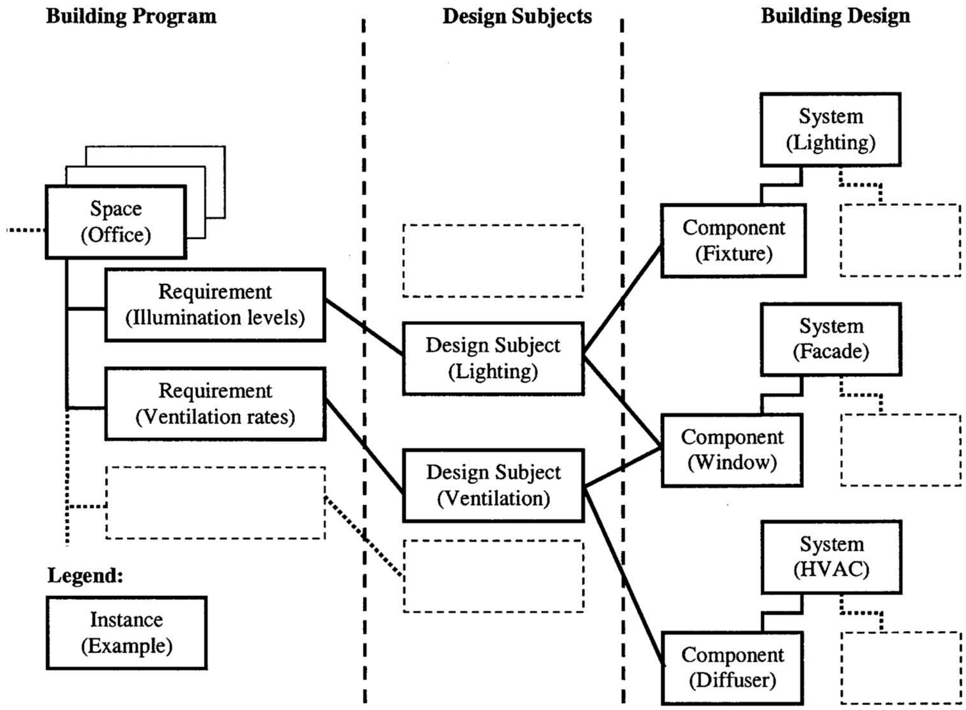

Fig. 2. Linking requirements with building components through design subjects

ventilation and any components that facilitate the latter requirement, such as certain components of an HVAC system (Fig. 2).

Implications of a Proposed Change on the Entire Project

Conventional building programs define the project requirements for the different spaces in the project but do not cover the various relationships between the spaces. Occasionally building programs include adjacency requirements that define the need for two spaces to be located next to each other, but other indirect relationships are usually not documented. Such relationships exist when both spaces serve as common activity or if a common building system is located in both spaces. For example, two spaces might be related because they serve subactivities of the same administrative activity, and they might be related because they contain components of the same HVAC system (Fig. 3).

The CCT relates the project requirements of different spaces in the building program to each other by tracing indirect relationships, and thus it identifies the implications of a proposed change in one space on the other spaces in the project. To facilitate requirement traceability tasks, the client requirements and the building design are represented in the form of graphs. A graph links activities to subactivities in the client requirements model and links components to their systems in the building design model. When a change is proposed that includes a certain component of a building system, other components influenced by this change are traced through the graph and the spaces in which these components are located are identified. In a similar way, the CCT traces related activities and the spaces to which they are linked. Thus, complex relationships can be automatically defined without active user input. For example, when the size of an office is increased, the user will be notified that this might affect the number of restrooms needed to serve this office, as well as the spaces containing components of the HVAC system that serves the office (Fig. 3).

Pilot Studies

The proposed model of the CCT was implemented, using Microsoft Excel, to examine its ability to identify the implications of a proposed change and to support the decision process in which this change was evaluated. The activities and components influenced by a change were traced using adjacency matrices, which represented the graphs. The rows and columns in the adjacency matrices represented the nodes in the graphs, and entries in the matrices indicated whether a link existed between the nodes. The links were thus traced automatically in the computer application, without intervention by the user.

Using the model, four pilot studies were conducted. One study was conducted of a college campus project, in which the drainage system was modified during construction. This change had several unanticipated implications on other building systems. A second study was conducted of an exhibition building in a science museum, in which a new activity was introduced. This change seemed minor when it was first proposed but later turned out to have major implications on the project.

Two other pilot studies conducted will be described here in detail. They included an infrastructure project (renovation of a water pumping station) and a building construction project (expansion of a maternity ward in a hospital). A description is presented below of a specific change that was introduced in each of these two projects and its actual implications, alongside a description of the identification, in retrospect, of these implications by the CCT model.

First Pilot Study: Renovation of a Water Pumping Station

This project involved the renovation of a water pumping station and included the building of a new reservoir, the installation of new water pumps, and the renovation of the electricity distribu-

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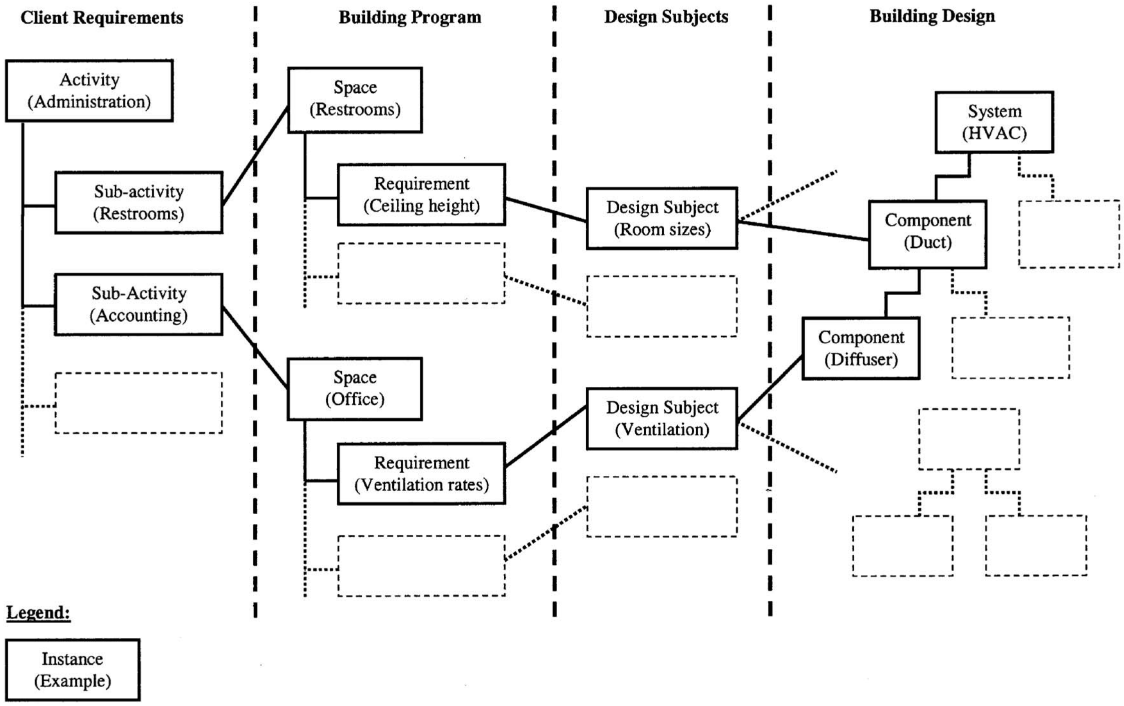

Fig. 3. Tracing indirect relationships between spaces

tion system. Since a shutdown could cause water shortage in higher locations, the client required the installation of a diesel generator, which could supply power during temporary interruptions of the utility power supply.

During construction, it was discovered that there was temporarily no budget for the acquisition of the new diesel generator. It was therefore decided that two old generators, already on site, would be used until a new generator could be acquired. The existing generators were moved to a new location and connected to the electricity distribution system. Later, it was discovered that the water supply to the utility during interruptions had been reduced because the power supply of the two old generators was less than that required by the client.

In the pilot study, the activities in the client requirements were documented in a graph (Fig. 4). For each activity, attributes such as the type of activity and required equipment were documented. Following this, the building program was documented, and each space in the building program was linked to an activity in the client requirements. In the building program, project requirements were added such as the area for each activity, the type of equipment required, etc. Information in the building design, such as the location and dimensions of the building components, was also documented and linked to the project requirements in the building program. The linkage was done directly and not through design subjects. In this project, the links between the requirements and components were relatively straightforward, since both related mainly to mechanical, rather than human, activities.

The tracing, in the CCT model, of the relationships between the different requirements made it possible to identify, in retrospect, the consequences of the change in the power supply. Thus, it was possible to identify the implications of the use of the two existing generators on the output of the water pumps by tracing the relationships between the different components in the electricity distribution system. The implications of the change in the output of the water pumps on the water supply were identified by tracing the relationships between the project requirements in the building program for the pump room and the client requirements for the water pumping activity. Thus, by tracing indirect relationships between the different requirements in the project, it was possible to determine that the water supply would be reduced as a result of the change that was made.

Second Pilot Study: Expansion of a Maternity Ward in a Hospital

This project involved the expansion of a maternity ward in a hospital. The changes that were made in the project caused an increase in its estimated costs. After the project design had been completed and the cost estimates and tender documents had been prepared, the client discovered that the project had become too expensive and it was put on hold. Currently, design is under way for an alternative, smaller project.

Stage One

Project Description. At the inception of the project, the client stated a requirement, among others, that the project should increase the number of delivery rooms in the ward by 100%.

Results with the CCT. The CCT model allowed a formal documentation of the client activities from which this project requirement was derived.

Stage Two

Project Description. After a building program had been prepared and an initial design was presented to the client, regulatory authorities introduced a new requirement: All of the delivery rooms had to be placed inside a protected space, designed to protect those inside from a conventional armed attack. This project requirement had many implications, which were gradually revealed as different members of the design team changed their

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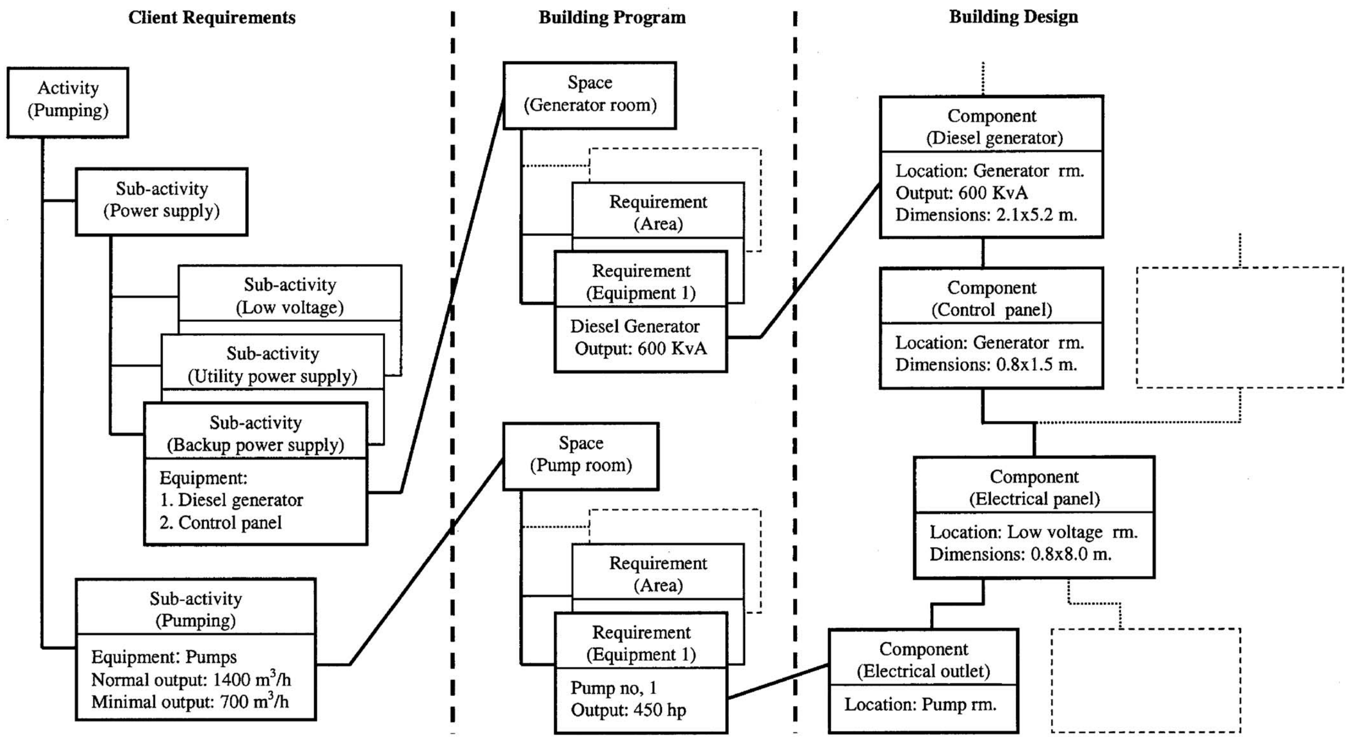

Fig. 4. Description of first pilot study with CCT model

design, as recorded in CAD documents. These implications involved different building systems, including HVAC, lighting, and, of course, the building structure. The facade of the protected space was required to be built of 30-cm-thick reinforced concrete walls. Because of the site topography, the delivery rooms were designed to be placed on the first floor, initially raised on columns above the sloping site. Eventually the structural engineer in the design team pointed out that these columns had to be turned into concrete walls in order to support the protected space above them. This would create a new space on the ground floor, enclosed by walls.

Results with the CCT. The CCT model indicated the implications of the proposed change on the design of the delivery rooms themselves by tracing the new requirement for a protected space to the components satisfying this requirement, including the exterior walls of the delivery rooms (Fig. 5). The model also traced other components and spaces influenced indirectly by this change, including the columns on the ground floor, which support the exterior walls of the protected space. Thus, the model indicated the implications of the proposed change at the moment it was introduced.

The timely appreciation of these implications could have led to a reassessment, in the original project, of the requirement for a 100% increase in the number of delivery rooms in the actual project. As in many other projects, the client's needs had not been formally analyzed and documented, and the project requirement for the number of delivery rooms was not put into question after it had been included in the building program. Using the model, the consequences for the client activities of a change in this requirement were evaluated, in retrospect. Thus, it was possible to investigate the implications of a decrease in the number of delivery rooms, introduced in order to offset the extra cost of the required protected space.

Stage Three

Project Description. The client suggested utilizing the new space on the ground floor, enclosed by the newly required supporting walls, for storage rooms serving the entire hospital. The project design was duly updated in the CAD documents, and the necessary building components were added, including floor pavement, lighting, fire-proof doors, and a fire sprinkler system mandated by the authorities.

Results with the CCT. When the change in the project scope was introduced in the pilot study, the use of the CCT model led to an evaluation of the need for this change and its implications, as it required a clear definition of the client needs. This ensured that questions were raised, such as, how much extra storage does the hospital need, and should the entire ground floor be utilized for this activity?

The use of the CCT model in the pilot study also required changing the building program to include the proposed storage facilities and specifying the project requirements for these spaces.

Finally, the CCT model linked the new project requirements to the components satisfying these requirements. For example, the requirement for fire safety was traced to various components such as fire-proof doors and a fire sprinkler system. This could have made possible, in the actual project, an assessment of the impact of the proposed change on the project cost.

Conclusions

This research proposes a new approach for coping with changes during construction projects: To develop a CCT that will identify the scope of the implications of a change as soon as it is proposed, in order to ensure that the stakeholders involved in the

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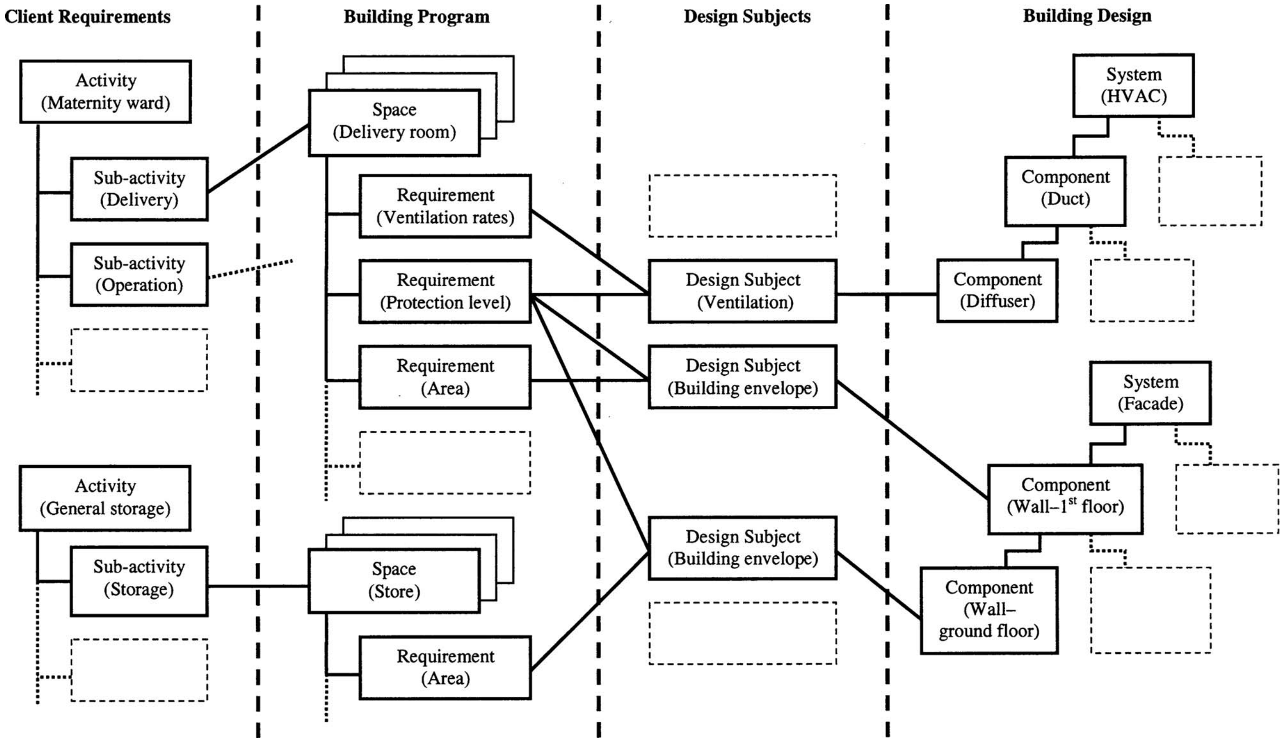

Fig. 5. Partial description of first pilot study with CCT model

decision process in which change proposals are evaluated will know in advance if a change could cause the project to stray from its original goals. A model for the CCT has been proposed, in which the building program serves as a link between client requirements and the building design and the different relationships that exist between the requirements in the project are traced. Pilot studies implementing a model of the CCT have yielded positive results, indicating that the CCT could identify, though in this case in retrospect, the impact of proposed changes. This might have prevented the negative consequences these changes had on the projects that were studied, which were not identified at the time. The pilot studies also indicated that the CCT might be feasible for various types of projects, both infrastructure and building construction projects. It remains, however, to further develop and test the CCT to reach final conclusions about its feasibility.

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