# An Information Model for Improving Design Coordination in Building Projects

by

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**A thesis**
**presented to the University of Waterloo**
**in fulfillment of the**
**thesis requirement for the degree of**
**Doctor of Philosophy**
**in**
**Civil Engineering**

**Waterloo, Ontario, Canada, 2000**

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# Abstract

Engineering design is a complex multidisciplinary process often constrained by time and money. The success of this process is highly dependent upon effective coordination among the diverse design teams involved. Despite its importance, coordination is neither simple nor error free and at present relies primarily on manual methods of cross checking. Such practice can thus be characterized as slow, costly, and ineffective. It is the objective of this research, therefore, to re-engineer the design process utilizing the recent advances in information technology and computer applications in order to facilitate coordination and increase productivity. The novelty of this research is in the development of a comprehensive model for efficiently representing multidisciplinary design information, recording design rationale, and facilitating the management of design changes. The model incorporates a unified hierarchical representation of the multidisciplinary design information. Building components are designed as intelligent objects that encapsulate their design rationale and appropriate communication paths. These components are able to automatically communicate any changes in their data to affected parties. The design rationale is represented for each component by recording the description of desired performance criteria, the minimum and maximum performance values, and the dependency relationships among components. The model also incorporates several design-change management procedures for proposing changes, sending changes, tracking changes, and following up on pending changes.

To facilitate the developments of this model, an investigation into the traditional design process was conducted by means of a questionnaire survey to document the flow of design information among the participants and to elicit some of the rules-of-thumb used by expert designers to improve coordination. To demonstrate the concepts presented in this research, a prototype of a collaborative system for design coordination was developed. The proposed prototype incorporates a client/server environment and Internet-based collaboration tools for sharing documents, reviewing changes, and conferencing among remote design participants. The prototype was successfully applied to a real-world example project to demonstrate the usefulness of the model and its capabilities over current practice. The opinions of expert designers on the prototype performance were then solicited and used to both refine its components and evaluate the usefulness of the model.

The perceived benefits of the developed model are expected to be improved design, higher consistency, increased productivity, and better constructability of projects. This research is expected to help design firms become highly competitive, nationally and internationally, within the open market economics being adopted worldwide.

# Acknowledgements

Many thanks are first offered to God.

I wish to express my deepest gratitude and sincere appreciation to my co-supervisor Professor Tarek Hegazy, for his academic as well as financial support. His continuous assistance, valuable advice, and constructive guidance throughout all the stages of this study are highly appreciated.

I wish also to express my deepest gratitude to my co-supervisor Professor Donald Grierson, for his unbounded support for this research both academic and financial. His practical comments and valuable advice throughout the course of this study are deeply appreciated.

Thanks to my colleagues in the University of Waterloo for the valuable discussions and their suggestions and feedback during this research.

I would like to thank Mr. Ralph Korchensky for all his assistance.

I would like also to acknowledge the financial support awarded to me through the Ontario Graduate Scholarship.

I wish to express my special thanks to my family; my wife, daughters, and son who have encouraged me, shared with me happy moments, and endured a lot of inconveniences along the course of this study.

Finally, I would like to dedicate this thesis to my father and mother who have been a continuous source of love and encouragement throughout my whole life.

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# Chapter 1

# Introduction

## 1.1 General

The design of building projects is an iterative multi-disciplinary process often challenged by tight budgets and limited time. Participants in the construction industry have also become aware of increasing problems of poor quality, resulting mainly from design (Burati et al. 1992). Undoubtedly, the quality of design has an extensive impact on all subsequent stages of a project's life cycle. In addition to proper tools and competent designers, producing a quality design is highly dependent upon effective coordination among the architectural, structural, mechanical, electrical, and the other teams involved in the process.

Most design coordination problems are embedded in design documents and may not be discovered until during construction. Some of the expected consequences are variation orders and contractual disputes, which lead to cost overruns and, often, client dissatisfaction. Unfortunately, with the escalating complexity in building projects, the broadening of disciplines involved in building design, and the tightening of financial and time resources available to designers, compatibility errors are increasing in the building design information presented in technical documents (Mokhtar et al. 1998, Tilley and Barton 1997). With the current fast pace of technological advances, design coordination becomes an essential element of success particularly within the prevailing market pressures on design firms to downsize, restructure operations, and work more productively and cost-effectively. Coordination, however, is not a simple task due to the multitude of interactions (some paradoxic) among the work done by the different teams. A vivid example is the task of determining floor heights by the architectural team when beam depths and mechanical ducts are not finalized by the structural and the mechanical teams, respectively. Current coordination methods rely primarily on manual methods of cross-checking and frequent exchange of drawings and documents. The results of this inadequate process are often delays, interference, rework, and cost overruns.

Many examples of good coordination are seen, and perhaps even unnoticed, in day-to-day life. Smoothly running flights in an airport, a well-organized conference, or a functioning assembly line are examples of how well coordinated the actions of a group of people seem to be. Often, however, good coordination is nearly invisible, and coordination is sometimes noticed most clearly when it is lacking (Malone and Crowston 1991). On a construction site, mismatches between drawings, inconsistent dimensions, and inconstructable details are situations frequently encountered and emphasize the effects of poor coordination. In recent years, therefore, there has been a growing interest in investigating how the activities of complex systems, such as the design process, can be coordinated (e.g., Huberman 1988; Johansen 1988; Rumelhart et al. 1986; Winograd and Flores 1986; Bond and Gasser 1988; Huhns and Gasser 1989).

For the purpose of re-engineering an interdisciplinary process such as design, a more precise definition of coordination needs to be made. Table 1.1 lists a number of diverse definitions suggested for this term by different researchers. For the purpose of this research, coordination is a summation of all these definitions to accommodate the tasks done by a single design team and among the multi-disciplinary teams. As such, it can be defined more formally as: "It is an environment in which the members of a design team work together in a collaborative manner that maintains consistency and productivity. Such environment effectively manages all interdependencies among the work of the various design teams in a manner that avoids discrepancies and contradictions throughout the whole design process".

**Table 1.1: Definitions of Coordination**

| Definition | Reference |
|---|---|
| Managing dependencies between activities | (Malone and Crowston 1994) |
| Activities required to maintain consistency within a work product or to manage dependencies within the workflow. | (Curtis, 1989) |
| The integration and harmonious adjustment of individual work efforts towards the accomplishment of a larger goal. | (Singh, 1992) |
| The additional information processing performed when multiple, connected actors pursue goals that a single actor pursuing the same goals would not perform. | (Malone, 1988) |
| The act of working together | (Malone and Crowston, 1991) |

## 1.2 Motivation for the Research

This research attempts to enhance and re-engineer the traditional design process and to improve design coordination. It also aims at assisting design firms in working more productively and cost-effectively with limited resources. The research has been motivated by several aspects including:

### 1.2.1 Design Process Fragmentation

The traditional engineering design process is highly fragmented (Teicholz and Fischer 1994). Howard et al. (1989) noted that such fragmentation is mainly due to the multi-disciplinary nature of the process in which each participant uses different tools and produces design documents that may not be properly coordinated with other disciplines and may not be consistent with a standard format as well. This often results in design interference, inconsistencies, discrepancies, omissions, and errors (Glavan and Tucker 1991).

### 1.2.2 Inefficient Methods for Communication and Exchange of Information

Traditionally, design coordination relies primarily on manual methods of cross-checking and frequent exchange of drawings and documents. Such practice, however, can be characterized as slow, costly, and ineffective (Hegazy et al. 1998, Mooney 1995, Teicholz and Fischer 1994, Dubois and Parand 1993). Moreover, the Architectural/Engineering/Construction (A/E/C) industry, with a few exceptions, is still using "paper" drawings and specifications to exchange project information (de la Garza and Alcantara 1995). As discussed in a number of papers (Howard et al. 1989, Tatum 1989, Vanegas et al. 1988), this practice leads to inefficiencies in the design and thus affects the overall quality of the construction.

The A/E/C professionals, however, have used computers as part of their work for many years (Logcher and Sriram 1990, Choi and Ibbs 1990) and still are widely using computers in most of their daily work due to current developments of affordable computer hardware and software. To a large extent, computers have been used to solve some of the independent problems faced by individual participants in the process, without being integrated in a consistent and unified system (Logcher and Sriram 1990). Other use has been limited to gathering and retrieving data common to multiple participants (e.g. CAD systems, management information systems, and database applications). In spite of their importance, these types of computer use did not change the nature of the design process, instead they led to new types of problems related to multiple versions and storage space requirements.

Using computers merely to produce paper documents is an inefficient way of utilizing this powerful technology (de la Garza and Alcantara 1995, de la

Garza et al. 1994). Present computer technologies, such as electronic mail and electronic file transfer, which allow the electronic exchange of information, are becoming increasingly accepted. Electronic information exchange can substantially increase the amount and variety of project information communicated as compared to the currently used traditional method of delivering it with paper. It is not only capable of conveying geometric information such as drawings, but can also transfer certain non-geometric information such as specifications, bills of quantities, and rationale. In addition to the e-mail technology, other new computer tools are also available which can effectively influence the way the A/E/C professions do business. These tools, undoubtedly, can be used to manage the overall design process in a more effective manner.

In addition to coordination, achieving and maintaining good quality in the design of projects depend on effective communication among diverse participants involved. With the dynamic nature of the design process, changes are frequently introduced and accordingly need to be well communicated to the affected parties. Poorly communicated changes in design may lead to inconsistencies and, therefore, modifications become costly and difficult to manage. In many situations, documents arrive late and/or contain changes that are unclear, misplaced, or irrelevant. The resultants of these situations are delays, cost-overruns, and poor constructability of projects.

### 1.2.3 Design Inconsistencies

Design inconsistencies, errors, or incompleteness occur during any stage in a project's life cycle. Inconsistencies in design may arise not only among the designs generated by the different teams but also within the individual team's design as well. On the individual team level, on the one hand, inconsistencies may arise due to inefficient office organization and unstructured team-coordination procedures, thus negatively affecting the quality of design. This is particularly so since changes during design are imminent as per owner's requirement or as a result of constraints in materials and methods. At the interdisciplinary level, on the other hand, teams' designs are often interdependent on one another. For instance, while the structural design requires the architect's space dimensions, the architectural design of windows and floors' heights is governed by the structural dimensions and mechanical duct sizes. Typically, each design team bases its design on initial assumptions of other teams' work as a start, and at a certain point, requires the detailed input in order to finalize its part of the design. Thus, if one team's data and/or changes are not promptly communicated to the appropriate team/s, modifications become costly and unclear.

### 1.2.4 Inadequate Design-Change Management and Miss-Representation of Design Rationale

In addition to its multi-disciplinary nature, the engineering design process is an evolutionary process. Designers typically generate several alternatives, one or more of which are developed (Krishnamurthy and Law 1995). The designs of different disciplines must be integrated to describe the overall project. Complexity arises in multi-disciplinary design situations because changes made in one discipline commonly impact design descriptions in other disciplines. For example, a structural engineer changing a beam depth may affect the mechanical engineer's HVAC duct depth and the architect's floor height. Furthermore, these changes are normally propagated through different levels of detail. Conflicts, inconsistencies, and mismatches, therefore, may occur if these changes are not properly coordinated and communicated among participants in different disciplines.

A design may be modified for many reasons during the design process. Previous decisions may need to be altered because of changes in specifications; changes in assumptions; or modifications in the designed building due to some client requirements. In addition, new designs can be generated by altering prior designs. Introducing design-changes for any reason, however, requires the designer making the change to be aware of the reasoning behind that particular design. This will assist in performing the required changes without violating any of the requirements or constraints of the previous design and, therefore, maintain consistency.

Design firms, however, do not have that knowledge adequately represented and organized in addition to the fact that many aspects of design description are not well-established (Bliznakov 1996). The design process of a construction project starts with the generation of a set of requirements or objectives that the design product must meet and ends with the production of drawings, specifications, and other construction documents. In the building construction industry, this process involves participants from all disciplines. These designers typically develop a set of drawings and specifications that depict the building graphically (such as in drawings) and textually (such as in specifications). Drawings, specifications, and other project documents, however, only represent the final results of the design process. These documents contain implicit information about the reasoning or rationale leading to the final form of the design. As discussed by de la Garza and Oralkan 1995, these information are hard to be detected and used by parties other than the designer himself. The current practice, however, does not provide adequate means of recording design rationale (Elam 1988, Howard 1991), in addition to the fact that the reasoning behind design decisions are informally recorded in a designer's notebook, if they are recorded at all. The lack of an adequate representation often causes part of the design knowledge to be lost.

### 1.2.5 Inadequate Document Management Procedures

As noted in the above section, design documents of a building project contain a large amount of data presented in drawings, specifications, bills of quantities, and other construction documents. Project documentation transfers various information to different project participants throughout the design and construction processes. Appropriate dissemination of this vast amount of project data, therefore, is central to project success. The current documentation systems used by engineering firms, however, do not provide adequate means of organizing and administering these documents and lack the appropriate management of multi-version CAD drawings normally produced during the design of multi-disciplinary projects.

## 1.3 Research Objectives and Scope

The primary objective of this research is to investigate the re-engineering of the traditional design process of building projects and to structure a collaborative environment that improves coordination and increases productivity of engineering design firms. The study involves four main aspects:

1- Investigating the traditional design process and identify problem areas and potential improvements.

2- Identifying the multi-disciplinary interrelations in design development and utilizing new advances in information technology and collaboration tools for the purpose of improving coordination and for better communication within the individual design team and among the multi-disciplinary teams.

3- Establishing a unified information model for representing design information, managing design-changes, recording design rationale, and improving design coordination procedures.

4- Developing a prototype based on the proposed model, demonstrating its capabilities on an example application, and validating its usefulness to design practitioners.

While this research focuses mainly on the design process of building projects, it can, with little effort, be adapted to other types of construction projects.

## 1.4 Methodology

The approach that was employed in this research in order to achieve the aforementioned objectives consists of the following (Fig. 1.1):

1- Analyze the traditional design process through surveys and interviews with practitioners to collect and model the procedures used by expert designers to coordinate design. This will help in documenting the flow of design information among the participants involved in the design process, identifying the interrelationships among the different building components, and determining the proper communication paths to affected parties when a change is introduced. It will also suggest a coordination scheme that will serve as a general guide for design firms to follow or change according to their own environment.

2- Establish a library of building components that can be used as a central storage of design data needed to describe a complete building project.

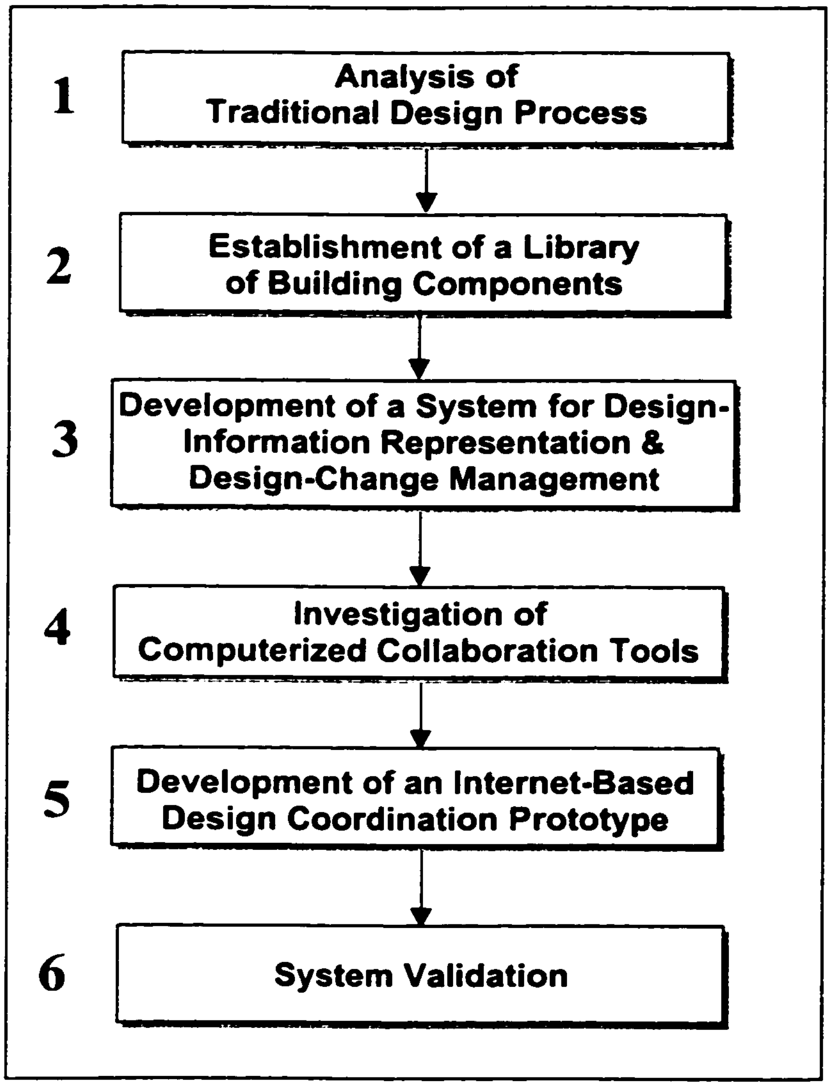


**Fig. 1.1. Research Methodology.**

3- Review of the available research efforts and the latest advances in information technology to represent design information, effectively manage design changes, and record design rationale.

4- Investigate the use of new advances in collaboration tools to provide a collaborative environment and a central access point for group discussions and share of information. This will help in achieving better team coordination and effective communication among different project participants in a design firm including remote parties.

5- Develop an Internet-based prototype of a collaborative system for design coordination. This prototype will facilitate a collaborative environment for a better coordination and communication between the project participants of the individual team and among multi-disciplinary design teams. Finally, proceed with the developments and validation of the system.

6- Implement the system on a real-life project to validate it and demonstrate its capabilities.

## 1.5 Thesis Organization

Chapter 2 presents a literature review of the state-of-the-art efforts that are related to the present study, these include: the traditional design process, design improvement programs, Internet and collaboration tools, models for representing design information, and design change management.

Chapter 3 presents the results of a questionnaire survey that was conducted among leading design firms in Canada to elicit experts' solutions to coordination problems. Based on the questionnaire survey, a design coordination scheme has been suggested and common interrelationships within the design development process have been explicated.

Chapter 4 describes the developments of an information model for storing multidisciplinary design information, recording design rationale, and effectively managing changes during the design of building projects. A central library of generalized building components is established for the use of all design participants to build a complete project.

Based on the structured information model presented in Chapter 4, a collaborative design system is developed in Chapter 5 incorporating a client server environment and Internet-based collaboration tools. Implementation issues are discussed in this chapter and an example application is then presented using the developed prototype to demonstrate its applicability and features.

Chapter 6 presents a real-life case study project obtained from a design firm to validate the system and demonstrate its practicality. A questionnaire is prepared to validate the various components of the system and obtain the feedback, suggestions, and evaluation of potential users. The result of the questionnaire is also presented in this chapter along with the evaluation and overall performance of the system.

Chapter 7 is the thesis conclusion and a description of future extensions to current research.

# Chapter 2

# Literature Review

## 2.1 Introduction

This chapter presents a comprehensive review of the state-of-the-art efforts described in the literature in several aspects related to the present study, these include: the traditional design process, design improvement programs, Internet and collaboration tools, models for representing design-information, and models for design-change management. This is for the purpose of identifying the procedures, among the many practices described in the literature, which are amendable to the re-engineering of the design process.

## 2.2 Traditional Design Process

It is beneficial for the present study to investigate the typical life-cycle of the traditional design process for building projects in order to be able to analyze the process and explore means of improvement. The design process, by nature, is an iterative, interdisciplinary, and multistage process. As viewed by Sriram et al. (1989a) and Tong and Sriram (1989), it is a six-step process: 1) identification of the design problem; 2) generating design requirements and performance specifications; 3) generating some preliminary designs that satisfy most constraints; 4) analyzing the response of the design system to external effects; 5) evaluating the solutions generated during the previous stages for consistency with the specifications to determine the best possible design; and 6) Detailing of the selected design and refining its various components so that all applicable constraints (or specifications) are satisfied. A re-analyses might be necessary, if significant deviations between the properties assumed or generated at the concept generation stage and those determined at the detailed design stage are found. The process continues until a satisfactory or optimal design is obtained. The accomplishment of this goal, however, is not a simple task and requires an extensive coordination effort at all levels of detail and among all participants.

The increasing complexity of the design process has been illustrated by Logcher and Sriram (1990) and Archer (1970) as a spiral process (Fig. 2.1). At each stage of this process, different designers get together periodically and set the design criteria and constraints, which must be met before proceeding to the next level of detail. Along the life-cycle of a traditional design (Fig. 2.2), the level of detail increases and accordingly the cost committed to the project and the ability to make cost-effective changes decreases. The early stages of the design process are the ones in which the major changes are made. As the process evolves, it becomes less cost-effective to change the decisions made at early stages. This is illustrated in Fig. 2.2 through the funnel effect (Kavanagh et al. 1978),

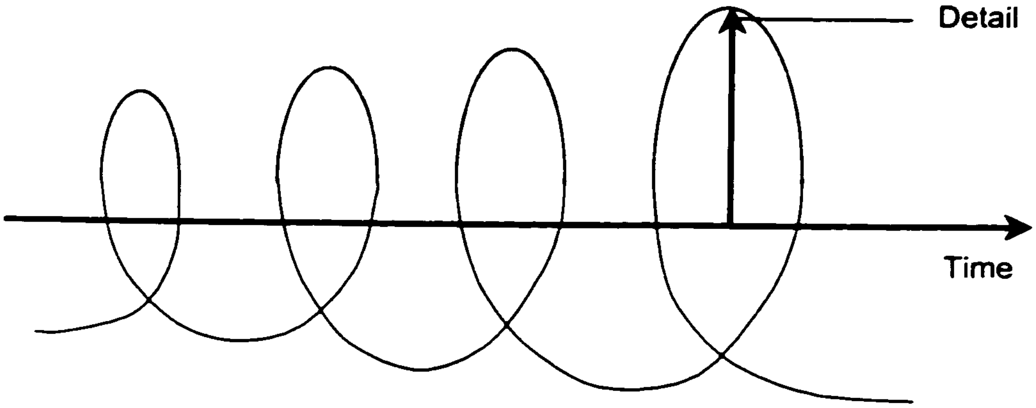
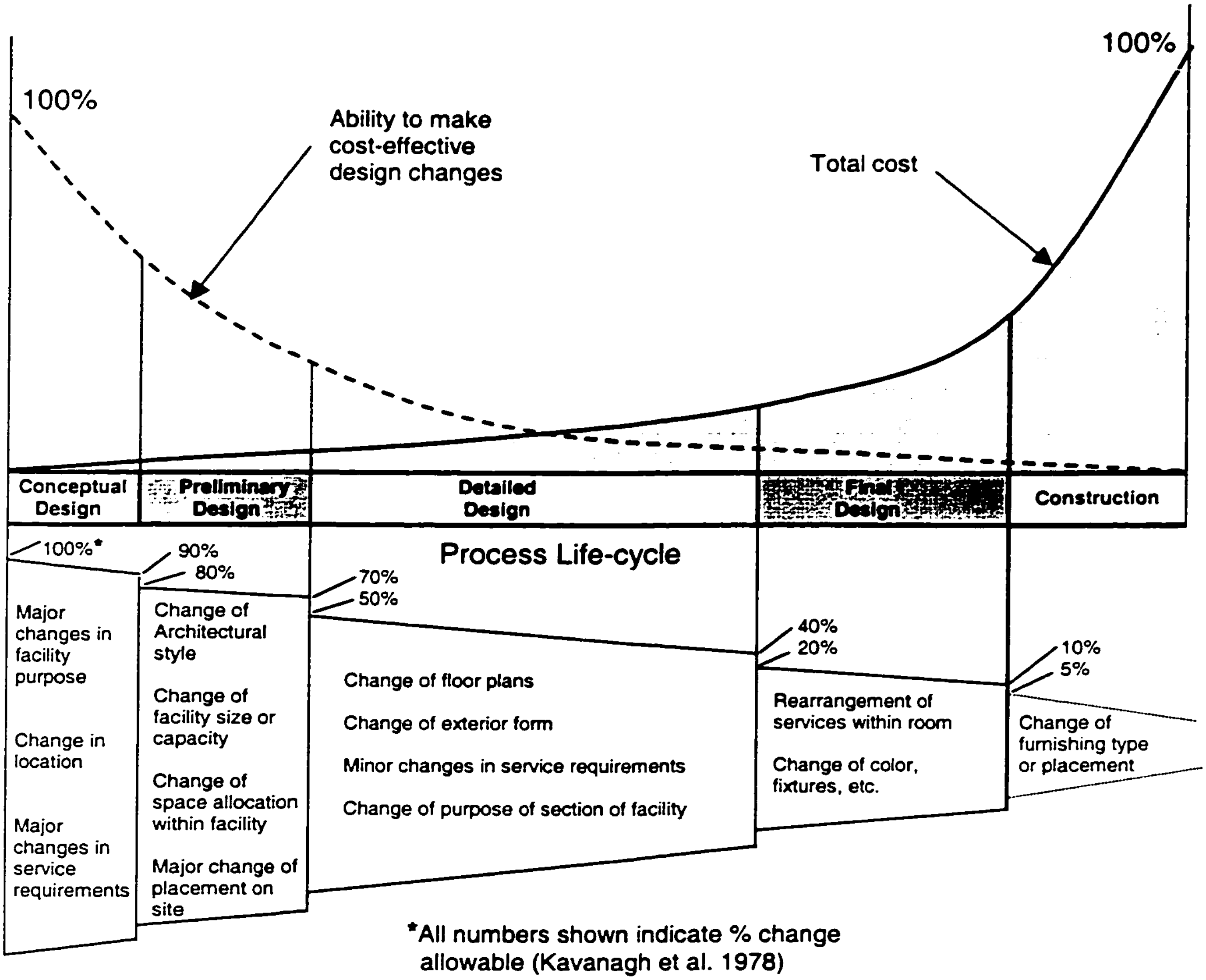


**Fig. 2.1. The Spiral Design Process (Archer 1970).**

showing the permissible percent changes at each design stage. It is, therefore, a worthwhile investment to spend the effort in generating high quality design (representing a low percentage of total project cost) that does not create problems at later stages where cost is very high and redesign is extremely expensive. Although the cost involved during the design is a small fraction compared to construction and maintenance, it is noticed that a great deal of care is often not taken in generating a highly coordinated design on the perception that corrective measures will be taken later, if necessary. The corrective action, however, is usually nothing more than a 'fix' to overcome a bad situation occasioned by a poor decision, leading to yet a "bad" design in some sense (Grierson 1997).



*All numbers shown indicate % change allowable (Kavanagh et al. 1978)

**Fig. 2.2. The Ability to Make Cost-Effective Design Changes.**

Technology can have a major impact in improving the efficiency of the traditional design process. The traditional and recent methods of performing design tasks are listed in Table 2.1. In addition to the importance of technology, the design process is an experience-based process in which the designers' experience is considered to play a major role in making design decisions. Also, a successful design, in the major part of current practice, depends more on the competence of people involved than on any procedure or tool. To optimize effort and circumvent problems, expert designers who have been exposed to many problem situations establish for themselves simple methods and rules-of-thumb for preventing mistakes, detecting mismatches, and effectively communicating changes (Hegazy and Khalifa 1996). Such rules-of-thumb are simple and beneficial to all participants in the design process. A survey among design experts, therefore, is necessary to identify common problems and areas of potential improvement in the design process before any re-engineering work can be performed.

**Table 2.1: Methods of Performing Design Tasks**

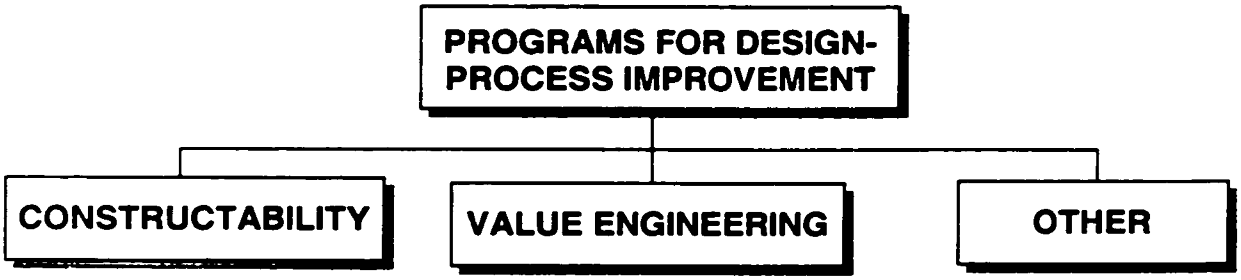
| Method | Traditional | Recent |
|---|---|---|
| Correspondence | Paper | Electronic mail |
| Drawings | Paper | CAD |
| Manuals, references, specifications, documents, etc. | Paper | Databases |
| Design-change management | Memos and periodical meetings | Same as traditional |
| Meetings and discussions | Face-to-face meetings | Videoconferencing |
| Problem solving | Experts | Knowledge-Based Systems (KBS) |

## 2.3 Design Improvement Programs

The complex nature of design, in addition to the lack of a systematic approach to maintain quality has contributed to the development of research in diverse areas related to design-process improvement. Constructability and Value Engineering, among other efforts, are two programs currently gaining wide acceptability in construction. A comparison among these design-process improvement programs is presented in Fig. 2.3. A common characteristic among these programs is their focus on the interaction between design, as a single product, and other phases of a project's life cycle, particularly the construction phase. This, however, seems to place less emphasis on the multi-disciplinary nature of the design development process. Design coordination, therefore, is an independent effort deemed appropriate to address the design development process and account for its unique difficulties and challenges (Hegazy et al. 1998). In this sense, design-coordination can be an important complementary task to all other design improvement programs, thus responding to many of the barriers to their effective implementation (Aaron 1996).

## 2.4 Internet and Collaboration Tools

The construction industry's tight budgets, time constraints, and the increased need to coordinate organizational activities across geographically dispersed locations have contributed to recent developments in communication and collaboration technology (Callahan et al. 1996; Cano et al. 1996). Among the recent computer advances that can undoubtedly have major impact on the design process is the Internet. The Internet is emerging as a revolutionary low-cost computerized tool for worldwide communications and sharing of information. It is particularly useful to support information-dependent processes, such as multi-



| | CONSTRUCTABILITY | VALUE ENGINEERING | OTHER |
|---|---|---|---|
| Description | Defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives (AACE 1992).<br>Focuses on **optimizing the construction process** in terms of construction cost, schedule, safety, and quality. | Defined as a multi-disciplinary, systematic, and proactive function that is targeted at the design itself. The objective is to develop an item or a facility that will yield the **least life-cycle costs** or provide the greatest **value**, while also meeting all functional, safety, quality, operability, maintainability, durability, and other criteria established for it (AACE 1992). | Computer-Integrated Construction (**CIC**).<br>Integrated Data Modeling and Product Modeling.<br>Documentation of Standards and Specifications. |
| Examples | Russel et al. 1994;<br>Eldin 1988; and<br>O'Connor et al. 1986. | Dell'Isola 1991; and<br>Basha and Gab-Allah 1991. | Teicholz and Fischer 1994;<br>Yamazaki 1992;<br>Yabuki and Law 1993;<br>O'Connor and Caraway 1993<br>Dubois and Parand 1993;<br>Evt et al. 1992; and<br>Wright et al. 1992. |

**Fig. 2.3. Design Improvement Programs.**

disciplinary design, that requires close cooperation among a group of diverse and possibly remote experts. The Internet can provide unsurpassed benefits to the design process. With its powerful ability of being easily programmable, Internet-based systems are perceived to provide custom solutions for design coordination and communication as well. Such systems can also be more practical when coupled with automated filing systems that keep track of file evolution and its multiple versions.

Though the construction industry has been slow to adapt new technologies, Internet is, by far, the fastest growing computer technology the construction industry has to catch up with. In the near future, the use of such technology will not only increase productivity and work coordination but will also mean the life or death of an organization as it becomes a key to reducing overhead cost and operating an efficient business (Hegazy at al. 1998). Although connections to the Internet are widely available, most companies have avoided using them to link remote locations and offices because of security concerns. However, with the introduction of new solutions to security and confidentiality issues, the Internet technology can be considered as a low-cost tool for effective communication among remote experts and can offer to a design office a lot more than the telephone and the facsimile technologies are providing today. In construction, several Internet-based applications have been developed to demonstrate the usefulness of the technology. These applications include bidding (Hegazy and Mokhtar 1995), communicating site control data (Seesing 1996), and Internet publishing of project-specific design data (Schriener and Phair 1996).

Larger numbers of people now have the opportunity to use the Internet to help coordinate their work. Newer versions of almost all software systems have included direct Internet access and have incorporated features to support multiple users working together on the same document, display and search for Internet information more effectively, and exchange electronic messages. It now appears likely that there will be a number of commercially successful hardware and software of this new type (often called "computer-supported cooperative work" or "groupware") evolving for electronic mail, group discussions, workflow, group scheduling, document management, and Internet access. These applications provide a significant paradigm shift in computer usage (Malone and Crowston 1991) that is highly desirable to be utilized to improve the design process. In the long run, the dramatic improvements in the cost and capabilities of information technologies are changing the means of communication and coordination. At the same time, there is a pervasive feeling today among design firms that global competitiveness is becoming more critical. Using these new tools, therefore, may help change the way engineers work together and coordinate their activities. Closer coordination among project participants in addition to cost-effective communication tools will, undoubtedly, help create organizations with highly productive project teams.

A variety of Internet-based software and hardware systems are being produced at an astonishingly fast pace. These systems cover a wide range of tools for individuals, small businesses and large enterprises who can tie their local or wide-area networks to the Internet, forming Intranets. With little cost involved, tools such as Internet telephones, videoconferencing, remote control, file sharing, chatting, white-board discussions, and document-transfer may be used, individually or combined, to provide custom solutions for design coordination and site-to-head-office communication as well. In addition to remote communication, Internet abilities to trace and document users' actions have direct application in the management of the many anticipated changes during design. Using the proper tools, a network administrator can monitor users' access times, the commands they use, and the changes they make. To facilitate that within a cooperative environment, several contact management and collaboration software systems have recently become available on the market, such as Lotus Notes, Novell's GroupWare, and Microsoft Exchange Server (Baum 1995). These systems provide general-purpose group scheduling, database management, and file sharing and have recently added Internet capabilities.

Lotus notes, for example, has become increasingly popular as a groupware platform since its beginning in 1989 as a client/server platform for deploying distributed workflow and communications applications (Dobson and Andrews 1995). Notes users can access multiple databases of documents, participate in electronic discussions, and route messages to quickly access and disseminate information. Novell, as another example, introduced a groupware alternative called GroupWise, incorporating a wide range of collaboration and document management features. GroupWare, however, lacks the ability to enable simultaneous distribution of information commonly known as database replication, which is one of the Lotus Notes features (Baum 1995).

Despite the powerful capabilities of these tools, they do not support the design-change management, which is an essential requirement to improve coordination. One of the major problems encountered while experimenting with Lotus Notes, for example, was that it could not track the full path for a certain component in a project hierarchy, which is a very important information needed when a change is made to that component. A full path for a "window" component, for example, is "a window in the living room of the ground floor of a house project". It is, therefore, important to utilize the useful features of collaboration tools and, at the same time, use a powerful programming language to provide the flexibility needed to facilitate other coordination requirements such as the management of design changes.

In addition to collaboration software, videoconferencing software are also gaining wide acceptability among many firms for its suitability to facilitate real time meetings and exchange of information while reducing travel time and cost. Microsoft NetMeeting, Gallant InterVision Pro, Diamond Supra Video Phone, Panasonic EggCam, Boca Video Phone, Tekram How-R-U, 3Com Bigpicture are examples of the commercially available videoconferencing kits, among many others surveyed and compared by Labriola (1997).

All these tools described in this section are affordable technology available for all design firms. The utilization of some of these tools will be investigated to provide a collaborative environment that will help in changing the design process by adapting the mentioned tools to the potential requirements of the design process.

## 2.5 Models for Representing Design-Information

The design of building projects is a complex task that involves vast amount of data, which must be organized so as to attain the desired quality (Galle 1995, Fischer and Froese 1996). This complexity has increased significantly over the past decades and is likely to do so into the next century (Froese and Waugh 1991, Fischer and Froese 1996). In part, it is possible to address such complexity by dividing design projects into tasks that are assigned to different designers. However, because these fragmented groups have difficulty coordinating their work and combining their contributions, inefficiencies arise in the project-delivery process (Howard et al. 1989). To overcome these inefficiencies, researchers and practitioners are investigating improved integration, i.e., the continuous and interdisciplinary sharing of data, knowledge, and goals among all project participants (Luiten and Tolman 1997, Fischer 1989). In the A/E/C industry, however, electronic information sharing has not been highly successful, since this has not been a major goal of computer applications. Rather, these applications have focused on automating individual engineering tasks, creating islands of information as illustrated in Fig. 2.4 (Hannus et al. 1995).

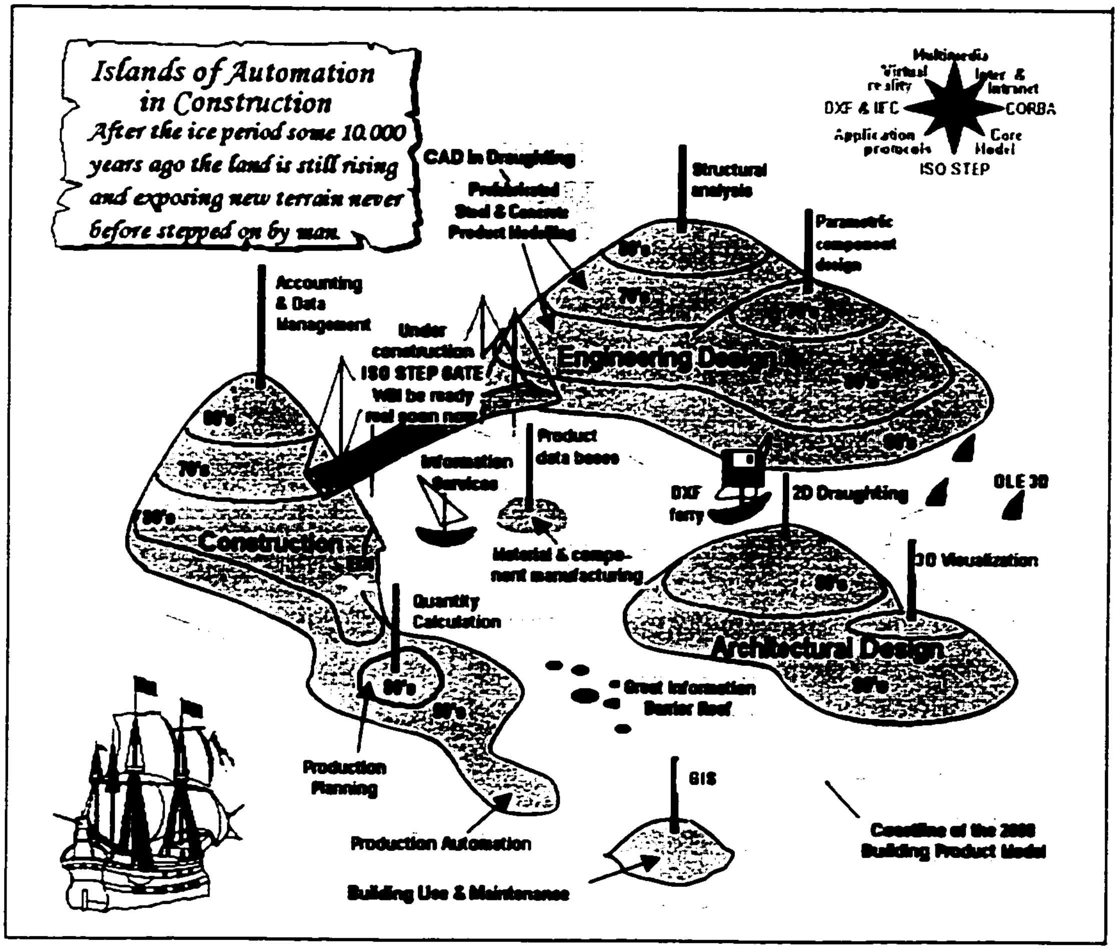


Fig. 2.4. Islands of Information (Hannus et al. 1995; Fischer and Froese 1996).

### 2.5.1 Early Efforts

Traditionally, design information has been exchanged through drawings and documents. However, many early attempts have been made to build models for easy storage, retrieval, and modification of building-construction data (Green 1966; Birgerson 1967; Ray-Jones and McCann 1971). This is paralleled by attempts to integrate building descriptions and provide a comprehensive model of buildings, sufficient for design and analysis. Accordingly, a set of prototype systems were developed in the mid-1970s. These include the SSHA-DOE Housing Model developed at the University of Edinburgh (Bijl et al. 1971), BDS (Hoskins 1973) from Applied Research of Cambridge, CEDAR (Sampson 1973) and HARNESS (Meager 1973), GLIDE and GLIDE-II by the University of Carnegie-Mellon (Eastman and Henrion 1977, Eastman 1980), and ARCH-MODEL from the University of Michigan (Borkin et al. 1981). Yet, these systems have not had a major impact in the practice of building and have been characterized as too complex and impractical (Eastman 1992). It was concluded at these early times that the development of a single building product model that can manage different systems interactions seems an impossible goal and can be too complex (Eastman 1992; Wright et al. 1992). This is because of the existence of so many properties and so many possible interactions that need to be embedded into objects, making them complex and very difficult to manipulate.

### 2.5.2 CAD Systems

Now, computers are increasingly becoming the primary medium for storing, processing, and exchanging project information (e.g., CAD drawings). Various standards such as DXF (AutoCAD 1990) have proposed formats for exchanging engineering data. These standards, however, target only the exchange of drawings, and require further work to enable a representation of engineering products (Baugh Jr. and Chadha 1997; Bloor and Owen 1991). The first generation of CAD systems used in building design was primarily aimed at automating the production of drawings to replace manual drafting. CAD systems have also provided the advantage of layering which helps in coordinating the work of various design teams to achieve a certain degree of integration between different disciplines. CAD drafting systems are capable of producing high-precision drawings and three-dimensional "geometric models". These systems, however, are general only by way of being "ignorant" about the buildings for whose creation they are used (Galle 1995). Yet, current CAD systems do not represent the relationship among the objects being drawn or among the object and other parameters that govern the rationale behind their geometric attributes. For example, two parallel lines close together can represent a wall in two-dimensional plan drawings, while they are simply lines without any relationship between them in ordinary CAD programs (de la Garza and Alcantara 1997).

### 2.5.3 Building Product Models

To build more intelligent models of buildings that allow higher level of integration among the design tools used at different stages and also among the various participants in the process, research on integrated standards and building product models has been pursued for the last ten years. This has been greatly motivated by recent advances in knowledge engineering and object-oriented programming techniques as well as increasingly powerful computer hardware. A schematic comparison of design and design documentation practice for the conventional design process and the process using a product model is illustrated in Fig. 2.5.

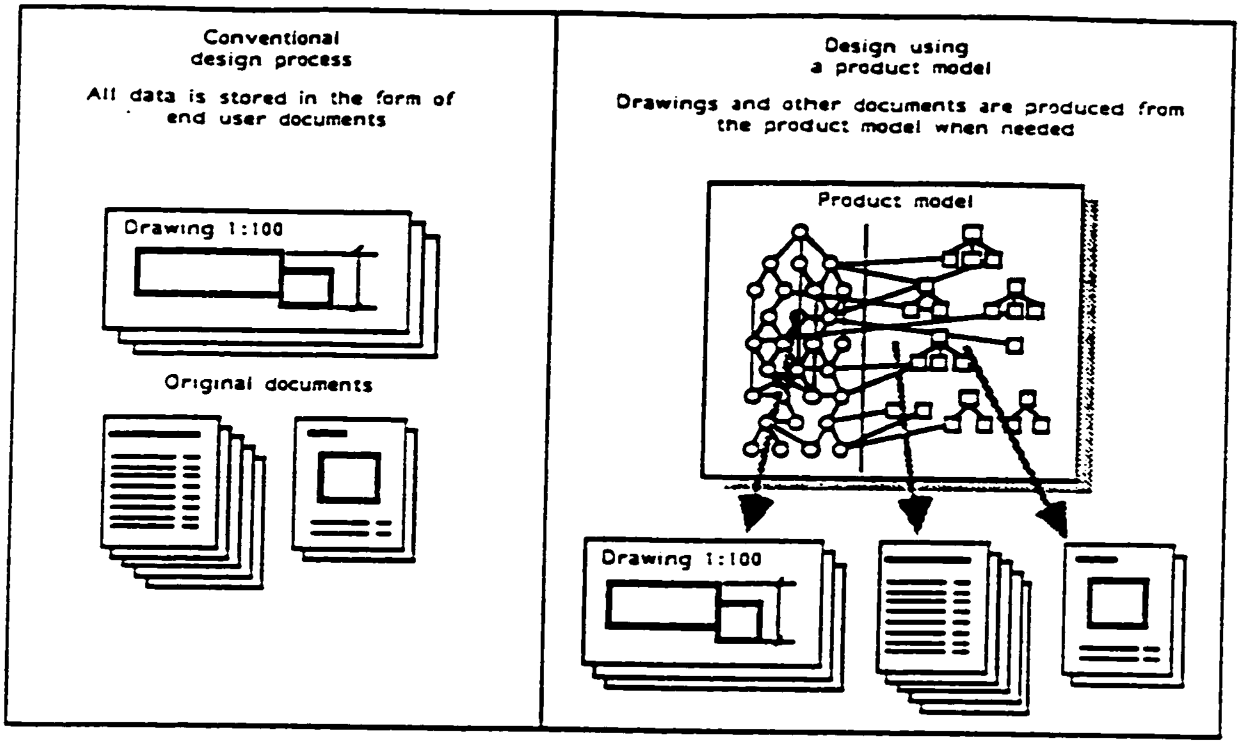


Fig. 2.5. A Schematic Comparison of Design and Design Documentation Practice for the Conventional Design Process and the Process Using a Product Model (Björk 1989).

The early standardization efforts focused mainly on the definition of product-model standards for organizing and translating data between different computer applications in engineering. Various conceptual models and international standards have been proposed to structure product models. The A/E/C Building Systems Model (Turner 1990) and the General A/E/C Reference Model (GARM) (Gielingh 1988) are two conceptual models, which were among the first efforts made to develop a comprehensive model for the building industry. Other conceptual models such as NIAM (Nijssen and Halpin 1989) and PANDA (Phan and Howard 1994) can provide a graphical language for product modeling.

The major standardization effort in product modeling today is ISO-STEP, the International STandard for the Exchange of Product-model data (ISO/TC184 1993). The purpose of this international standard is "to specify a format for the definition and exchange of computer-interpretable product information throughout the life of a product" (Luiten and Tolman 1997). STEP's development started in 1984 and builds on the Product Data Exchange Standard (PDES) (Smith 1986). STEP contains general-purpose data models, applicable to any field of design and manufacturing (Wilson and Kennicott 1987), as well as applications-oriented data models (Gielingh 1987). Examples of recent product models include the RATAS building model (Björk 1989, Björk 1994), COMBINE (Dubois and Parand 1993), CIFECAD (Kolountzakis and Fischer 1991), EDM (Eastman et al. 1991), IBDE (Fenves et al. 1990), DICE (Sriram et al. 1989b), and ICADS (Pohl 1991).

In essence, building product models are used not only to store geometric information about buildings and the relationship among these information, but also to record other non-geometric information such as design rationale. As described by Tolman and Gielingh (1988), building product models represent this information in the form of aggregation/decomposition hierarchies, generalization/specialization hierarchies, or a combination of the two hierarchies (e.g., Fig. 2.6). In aggregation/decomposition hierarchies, an entity (smallest component) can be part of an aggregation at a higher level while being decomposed into other entities at a lower level (for example, in a structural system, the "Piles" under "Deep", "Foundation" in Fig. 2.6). On the other hand, an entity in the generalization/specialization hierarchies can be a special case of a higher level entity while being a generalization of many lower level entities (for example, the "Beams" of Fig. 2.6 that are part of the "Horizontal" components of the "Building" while containing two entities "Structural" and "Tie").

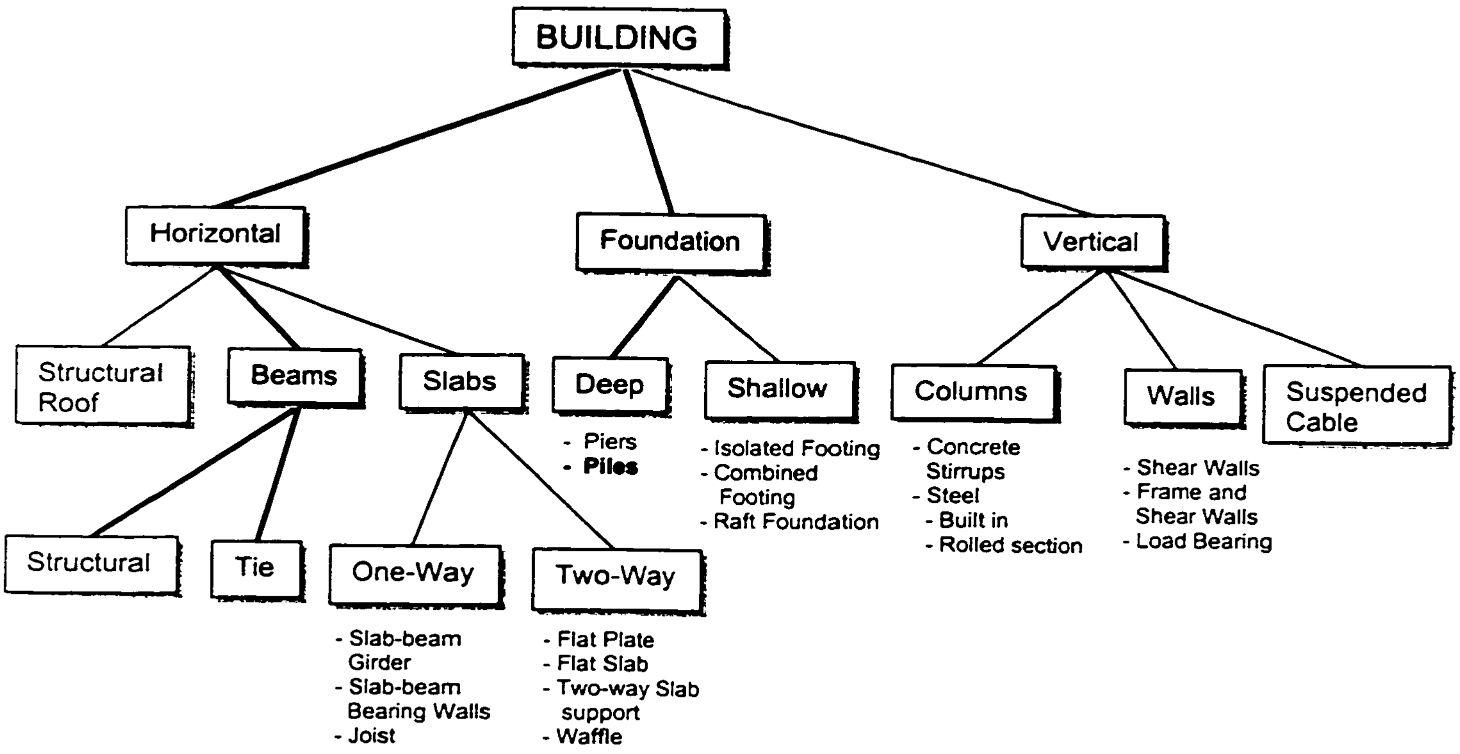


**Fig. 2.6. Data Representation in Building Product Models. (An Example of a Structural System Hierarchy, Evt et al.1992).**

Some of the research efforts on the development of building product models are as follows:

- The RATAS project (Björk 1989) involved developing an object-oriented product model to be used by different participants in the building process. The objective of this model is to develop a building product model that contains the most essential building objects with the most essential attributes. The RATAS model describes each building in a project as a hierarchy of objects. As illustrated in Fig. 2.7, five levels are used in the RATAS system: 1) building level: includes one object for the whole building with attributes that describe the site, the type of building, the building size, the construction cost, etc.; 2) system level: includes objects that contain general information about the different systems of the building (e.g., structural, mechanical, electrical, etc.); 3) subsystem level: includes objects that contain subdivisions of the system level objects (e.g., floors, wards, etc.); 4) part level: includes the majority of the building objects, such as spaces, walls, doors, and windows. Typical attributes for all part-level objects are location and shape; and 5) detail level: includes subdivisions of part-level objects (e.g., parts of a window or a door). The attributes of any level objects can be numeric values, text, pictures, or codes.

In the various prototypes developed based on the RATAS model, a relational database (ORACLE) is used to model the relations between objects defined in the product model (Fig. 2.8). One of the advantages of this system is that each item of information is defined only once, avoiding many problems that occur in today's manual practice.

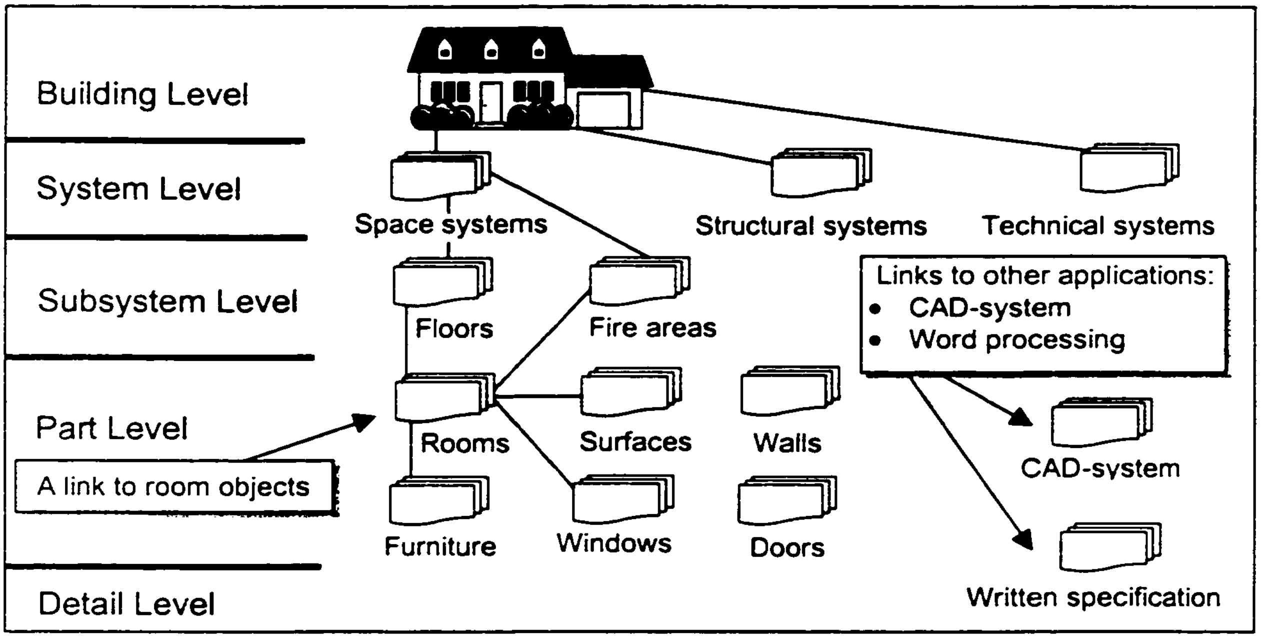


**Fig. 2.7. The Hypermedia User Interface of the RATAS Model (Björk 1993).**

- A prototype of a building product model is presented in Evt et al. (1992). As illustrated in Fig. 2.9, three orthogonal levels are used for storing building-project information: 1) level discriminators (levels of detail) which are used to distinguish various levels of objects in the building hierarchy; 2) discipline views to identify aspects of different disciplines (architectural, structural, mechanical, and electrical) for the same object; and 3) process stages such as planning, design, and construction stages that require different kinds

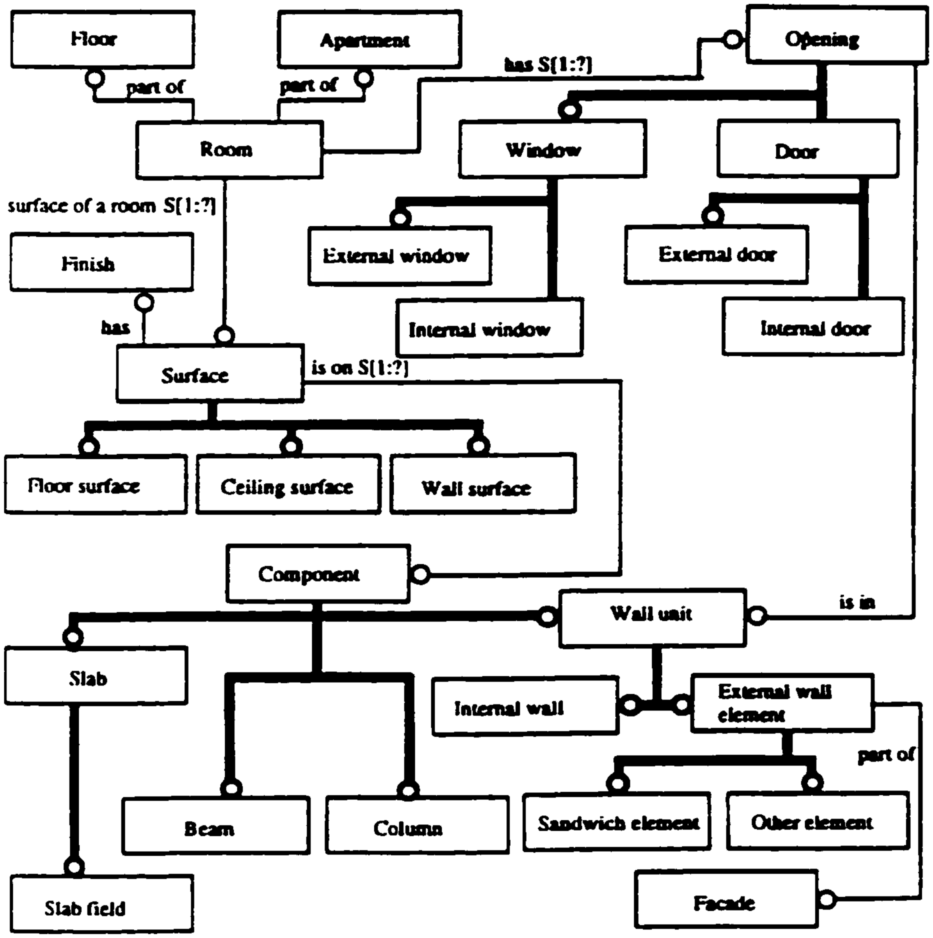


Fig. 2.8. RATAS Hypermedia-Relational Database Prototype (Björk 1992).

of information and resources. Information about each object has the attributes of function, form, economy, and time. While this model is interesting in simplifying the product model representation, its implementation on large-scale projects involved many problems due to the limitations of hypercard. This is in addition to the absence of a direct access to a database system and the large memory requirements.

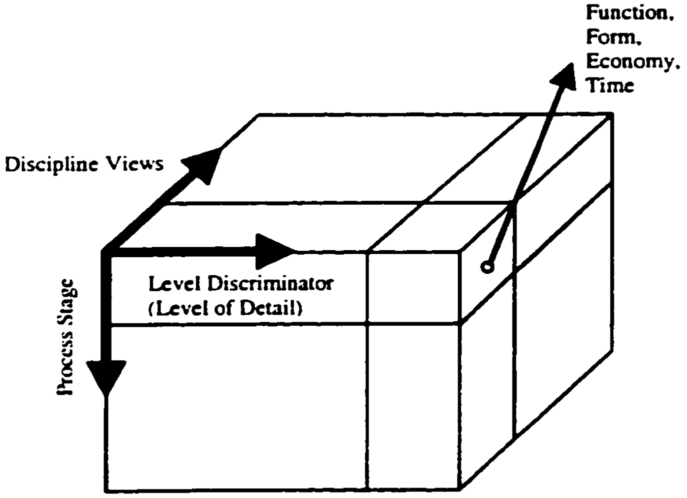


**Fig. 2.9. The Orthogonal Levels Used for Storing Building-Project Information (Evt et al. 1992).**

- Wright et al. (1992) proposed an interesting concept of Local Product Models that provide the possibility of sharing data between related application programs in building design. The Local Product Model is intermediate between a completely specialization model and a completely generalized model. This is because specialized building product models are limited to certain applications while generalized models seem to be impractical due to their complexity. Object-oriented programming (OOP) is used for integrating several applications. Objects are stored and exchanged between applications using an object-oriented database (OODB).

- The **CO**mputer **M**odels for the **B**uilding **IN**dustry in **E**urope (COMBINE) (Dubois and Parand 1993), is a coordinated effort to develop an Intelligent

Integrated **B**uilding **D**esign **S**ystem (IIBDS). In the first phase of the COMBINE project, a prototype software was developed for file exchange among various application programs related to energy and HVAC performance evaluation. In the second phase, an integrated data model (IDM) was used as a basis for the development of an integrated building design system that is aimed to be used in practice. The COMBINE project, in general, has the "project" as the main object that contains one or more buildings. The building is an assembly of systems: spatial system, fabric system, technical system, functional system, and external environment system.

- Avoiding the complexity of generalized building product models, Dias (1996) proposed an alternative building product model to combine only the architectural and structural information. This seems to simplify the representation and leaves the other aspects such as electrical and mechanical to be handled in other ways not necessarily in the same model. In his model, the entities of a building are placed at the levels of systems (e.g., architectural, structural, and services), subsystems (e.g., floors, shafts, rooms, circulations, etc.), and primary elements (e.g., spaces, openings "such as doors and windows", finishes, solids "such as beams, columns, and walls", etc.). The model mainly supports the quantity take-off and design checking processes. However, the model only covers architectural and structural systems and did not address other design disciplines.

- Fischer and Froese (1996) presented a system for the integration of computer applications using a shared project model. The main interesting feature of this system is its link to an external **CO**nstruction **K**nowledge **E**xpert (COKE) system to provide the designer of reinforced concrete buildings with an automated constructability feedback. The COKE system guides the designer in the preliminary layout and dimensioning of structural elements and, as such, it contributes to the sharing of knowledge between professionals involved in the design and construction phases. Although the shared project model can contribute to increased productivity and quality in the project-delivery process, it is limited to a particular application and still needs to address the interdisciplinary nature of the design process.

### 2.5.4 Documenting Design Rationale

The hierarchical representation of design data, such as that used in building product models, is beneficial to the present study. It can be used to record the design rationale that is fundamental to the development of the proposed system for design-change management. Design rationale includes the reasons in favor of the production of a given design description as well as the reasons against other possible design solutions. Reasons may be justified on the basis of design theory, design practice, codes, standards, client requirements, desired functional characteristics, required performance criteria, designer's style, and so on. Such reasons play a major role in the design of all building spaces and building elements. The importance of recording the design rationale information is that they are usually trapped in the design stage of the project and not transferred to other stages. Even within the same design stage, later iterations of a design often do not have access to the intent underlying the design made at previous iterations. This makes the implementation of changes very difficult and does not ensure that newly changed components are consistent with the original design intent. Since this information is not typically recorded, they seem to get lost by the time the design is complete. While the design rationale is actually embedded in the properties of design elements and their inter-relations, however, it is implicit and difficult to be inferred and used by parties other than the original designers themselves.

The term "design rationale" has been referred to as synonymous with other terms used in various communities (Table 2.2) and accordingly has been given various definitions (Table 2.3).

**Table 2.2: Different Terms Synonymous With Design Rationale.**

| Community | Used Terminology | Reference |
|---|---|---|
| Artificial intelligence community | • Design history<br>• Design rationale | • (Mostow 1985)<br>• (Lee and Lai 1991) |
| The standard for the exchange of product-model data (STEP) Standardization community | • Design Intent | • (Ullman 1994) |
| The commercial and industrial businesses community | • Corporate memory | • (Ullman 1994) |
| Other | • Product evolution | • (Chandrasekaran et al. 1993) |

**Table 2.3: Various Definitions Related to Design Rationale**

| Term | Description | Reference |
|---|---|---|
| Design rationale | Explicitly expressing the requirements, preferences, and reasoning implicitly embedded within the design drawings and specifications. | (de la Garza and Alcantara 1997) |
| Design rationale | An explanation of why an artifact is designed the way it is | (Lee and Lai 1991) |
| Design intent | The rationale behind the decision-making process during design | (de la Garza and Oralcan 1995) |
| Product evolution information | The blueprint for the evolution of the requirements into the production specifications. This blueprint not only has information about the development of the geometry, but also on the evolution of the product function and behavior, the rationale underlying design decisions, and the influence of business activities | (Ullman 1994) |
| Product evolution information | The body of information that explicitly records design activity and the reasons for making choices (and reasons for not making some choices) | (Chandrasekaran et al. 1993) |
| Product evolution information | Statements of reasoning underlying the design process that explain, derive, and justify design decisions | (Fischer et al. 1991) |
| Design history | A useful abstraction of the design process | (Mostow 1985) |

The most direct solution to recording design rationale is that designers generate a design rationale document to be added to the project's specifications, bills of quantities, and drawings. However, such a document only creates another source of confusion in design interpretation (de la Garza and Alcantara 1997, Chandrasekaran et al. 1993). The use of computerized product modeling techniques, therefore, can assist in reducing this confusion by integrating graphical information (e.g., drawings) and non-graphical information (e.g., specifications).

Some of the research efforts on the development of recording design rationale are as follows:

- The **I**ssue-**B**ased **I**nformation **S**ystem (IBIS) method (Rittel and Webber 1973) is probably the earliest and most referred to approach to describe the design process (Bliznakov 1996). It considers the design process as a negotiation process between different participants (e.g., designers, managers, clients, etc.). A design problem is represented as a sequence of issues. The IBIS method can record and play back some information generated during the initial stages of the design process, but it fails to capture the process as a whole (Jeon et al. 1994). It is successfully applied for description of software development process (Yakemovic and Conklin 1989, Yakemovic and Conklin 1990).

- Knowledge **Ac**quisition **L**anguage (SALT) (Marcus and McDermott 1989) is a tool for creating expert system rules, which are updated during interviews with the domain experts. The expert system proposes a value for one parameter of the design at a time and checks if each parameter satisfies all constraints. SALT allows users to create and maintain expert systems by checking the consistency of a new piece of knowledge with the existing knowledge base. It keeps track of how each new piece of knowledge added will fit with what is already in the knowledge base and warns the user of any inconsistencies that might occur because of the new knowledge addition. SALT then provides mechanisms allowing users to resolve the inconsistency, thereby ensuring the overall integrity of the knowledge base.

- Garcia and Howard (1991) presented a design rationale documentation tool named the **A**ctive **D**esign **D**ocument (ADD). It contains a fixed and pre-defined set of relationships between the various design parameters (such as heating capacity, primary heating system, and winter design temperature). ADD starts with a pre-defined but modifiable set of rationale information and captures additional design rationale when an expected value provided by the original rationale database differs from the current design. The domain of this system is mainly the preliminary design of HVAC systems for commercial office buildings.

- The **S**kull **O**bject **S**pace (SOS) (de la Garza and Oralkan 1992) is an interesting system to capture design rationale for the building construction cost estimating using hierarchical representation. It consists of six object libraries where both design and design rationale information are stored: building library (Fig. 2.10), space library, building assembly library, building component library, specification library, and material and equipment library. SOS uses a rule base to perform inferences on its object-oriented data structure, which constitute design rationale.

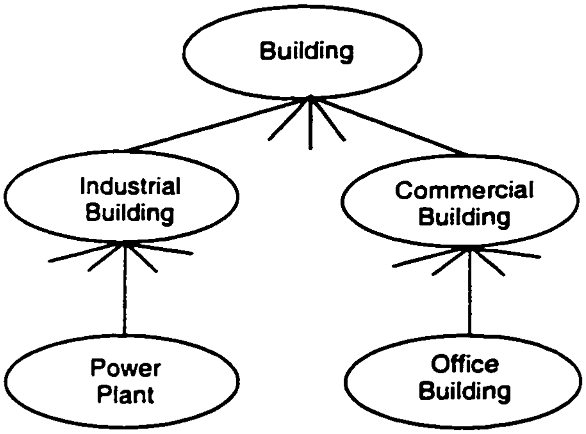


**Fig. 2.10. SOS Building Library (Alcantara 1996).**

It uses a four-level hierarchy in capturing design rationale: 1) building level: contains functions and user requirements of the building; 2) space level: contains functions and user requirements of building spaces; 3) building assembly level: contains performance information about the various building assemblies; and 4) building component level: contains physical property information about the various building components. Although this system was developed for use in building construction cost estimating, its hierarchical representation and semantic network (Fig. 2.11) are beneficial to the present study.

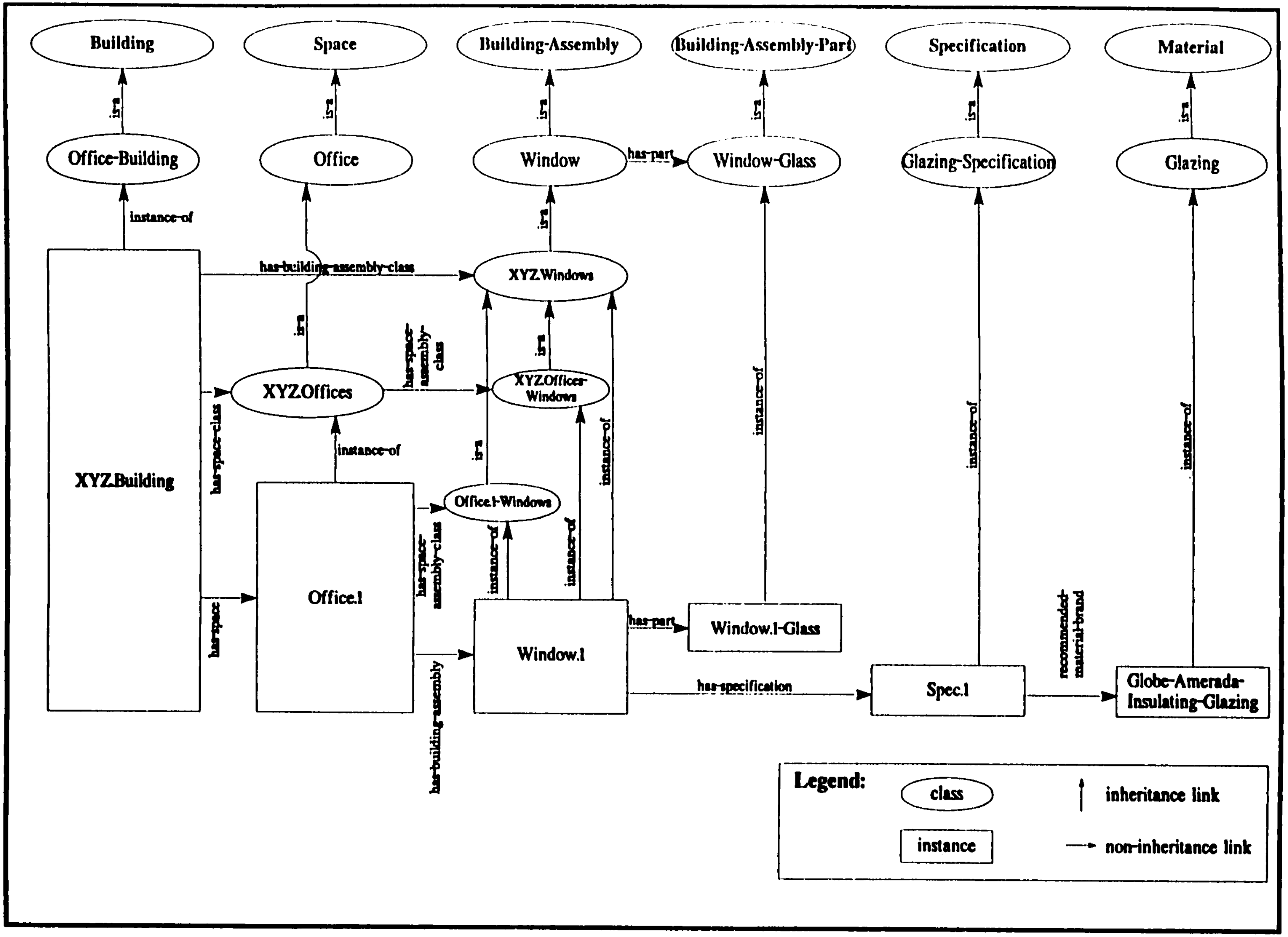


Fig. 2.11. Abbreviated Inheritance and Relational Semantic Network for an Example Building (de la Garza and Oralkan 1992).

- Another system for capturing the design intent is presented by Ganeshan (1992). It provides a record of both 'how' and 'why' the initial specifications are implemented in the final form of the product description. The approach has the advantage of recording the sequence of the decision-making process so that decisions affected by a change can be determined. The applicability of this approach, however, is limited to cases when design space can be characterized in a computable way. It also assumes a single designer-single task situation, which makes the approach not valid for use in multi-disciplinary environments.

- Jeon et al. (1994) used a database technique to capture design history. He uses an object-oriented model of data that includes four categories: 1) specifications of the artifact to be designed; 2) the sequence of design steps; 3) the relationship of design steps to design specification; and 4) the rationale for design steps. The data model is only affected by the purpose for which the system is going to be used. He specified five potential applications of the system shown in Table 2.4.

**Table 2.4: Potential Applications of Design Rationale Record Systems**

| | Use of the System | System Specifications |
|---|---|---|
| 1 | Design Reuse | Examine previous designs to determine the specific steps that occurred in the design process, the rationale and constraints that affected design decisions, and the versions and alternatives of the design specification |
| 2 | Analysis of the Design or Design Process | Review and analyze design history to determine where bottlenecks are, or to study why the design failed or why a certain alternative was chosen over others |
| 3 | Design Learning | Provide the novice designers with design assistance by classifying and maintaining designs in a design library |
| 4 | Versioning/ Configuration Management | Provide the capability to maintain various versions/configurations and alternatives of designs with their differing characteristics, design rationales, and justifications. |
| 5 | Design Maintenance | Provides a way to backtrack to a previous design state and to iterate over some part of the design with changed design parameter values |

- The Reviewer's Assistant (East et al. 1995) assists in the design review process. It uses a case-based reasoning approach. The tool assists reviewers by capturing, storing, and retrieving design-review comments, and compiling lessons learned. It is essentially a growing database of comments about the various building components of several different projects. The system, however, captures the rationale during a design review and does not capture it during the actual design process.

- Pena-Mora et al. (1995a) presented a **Design Recommendation and Intent Model (DRIM)** which represents the design rationale of an artifact. Designers, however, have expressed concern about spending time inputting the rationale. Taking this into account, Pena-Mora et al. (1995b) presented the

SHARED-DRIMS (SHARED-**D**esign **R**ecommendation and **I**ntent **M**anagement **S**ystem) which uses domain knowledge, past designs, and interaction with the designers to capture design rationale. The system generates some of the design rationale without asking the designer for it by searching for similar recommendations produced in previous designs. SHARED-DRIMS checks design decisions for consistency with the stored design rationale information in the database and notifies all interested participants of any design inconsistency. SHARED-DRIMS is a part of the **D**istributed and **I**ntegrated environment for **C**omputer-aided **E**ngineering project (DICE) which uses a network of computers having a global object-oriented database.

- de la Garza and Alcantara (1997) presented an interesting data structure that uses a parameter dependency network (PDN) to capture design rationale. The PDN uses the **D**esign **R**ationale for the **I**nformation Phase of **V**alue **E**ngineering (DRIVE) which aims at assisting value-engineers in gathering necessary information to suggest cost-saving and equal performance alternatives about an existing design (Alcantara 1996). DRIVE starts with a totally empty rationale database and relies on the user to create relationships among its various object-parameters to reflect rationale for their design decisions. It uses two modules: a design knowledge representation module (KRM) and a rationale storage module (RSM). The KRM consists of four building project hierarchies (building, spaces, assemblies, and components), four building construction libraries (building, spaces, assemblies, and components), and a performances library. The RSM (Fig. 2.12), on the other hand, contains all the design decisions about the different properties of the various design entities in the KRM.

Fig. 2.12 shows the semantic net representation of the RSM. The dependency_type link determines whether the rationale depends on other object-attributes while the relationship_type link determines the types of relationship relating the various object-parameters. The depends_on and has_relationship semantic net links generate the PDN. Although the system is mainly aimed at assisting value-engineers, its knowledge representation and rationale storage modules are interesting and can be beneficial to this study.

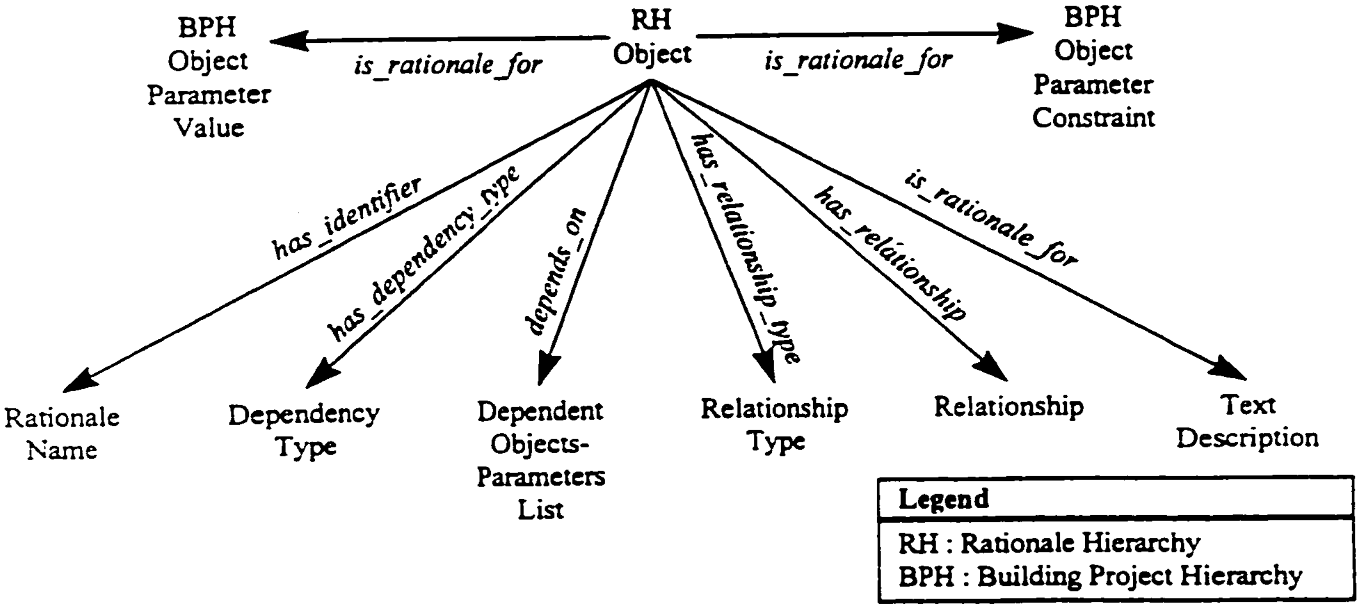


**Fig. 2.12. Semantic Net Representation of DRIVE's Rationale Storage Module (de la Garza and Alcantara 1997).**

## 2.6 Design-Change Management

Challenged by growing competitive pressures, the A/E/C industry, among others, have been looking for ways to improve their business processes by reducing costs and by improving quality. To accomplish this goal, researchers during the past decade have developed products and tools to support processes in design and manufacturing (Johnson 1989). The existing data management systems have largely focused on activities such as tracking design files, restricting access to such files, maintaining past versions of files, controlling the update process, notifying users of file changes, and performing electronic sign-offs.

These systems, however, have not addressed managing and coordinating processes in dynamically evolving collaborative environments. Among other processes, the engineering design process is typically the result of a multi-disciplinary collaborative effort. Designers from different disciplines independently develop aspects of a project according to their individual perspectives. These individual designs are then gathered to describe the entire project. For example, a building includes an architect's floor plan, a structural engineer's framing system, and a mechanical engineer's ducting and piping systems, among others. Furthermore, a design in a particular discipline is further described by its own component entities. A particular structural frame, for example, is described by aggregating its components, including specific beams, columns and slabs. In a multidisciplinary environment such as the design process of building projects, changes are eminent and need to be managed. Administrating these changes, therefore, is a key point in controlling the project and insuring a consistent and well-coordinated design. Moreover, during the early stages of the design process, changes can be made at minimum cost and have the greatest potential for maximum savings. In general, the earlier downstream parties are involved in the design process, the greater the potential savings that will be realized, as shown in Fig. 2.13.

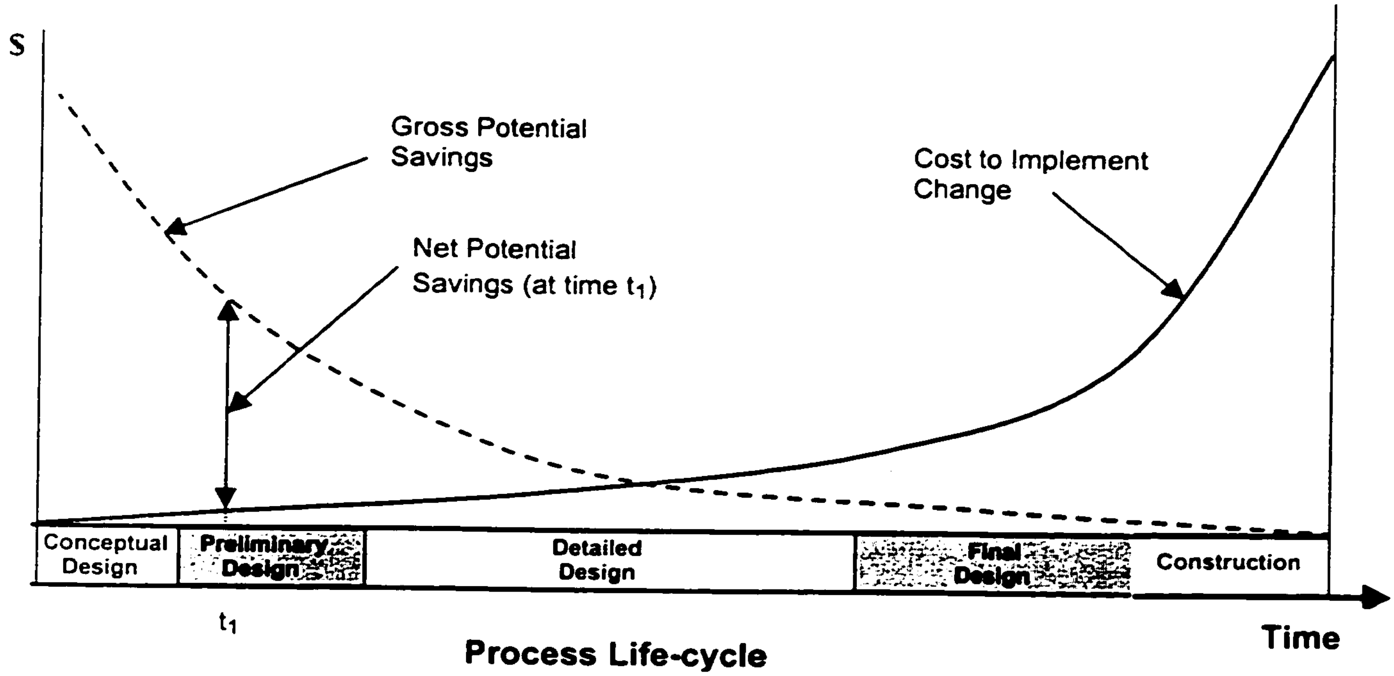


**Fig. 2.13. The Time-Value of Changes During Facility Delivery (Bearup 1995; Dell'Isola 1982).**

Limited research work have been made to investigate the problem of managing and coordinating design changes among all participants in a particular project.

Some of the research efforts related to the management of design changes are as follows:

- Distributed and Integrated environment for Computer-aided Engineering (DICE) (Sriram et al. 1989b; Ahmed et al. 1992) is a network of computers and users which consists of a blackboard (global database), several knowledge modules, and a control mechanism (Fig. 2.14). The DICE blackboard contains a version management system, which keeps a record of object changes but did not emphasize on the management of design changes (Krishnamurthy 1996).

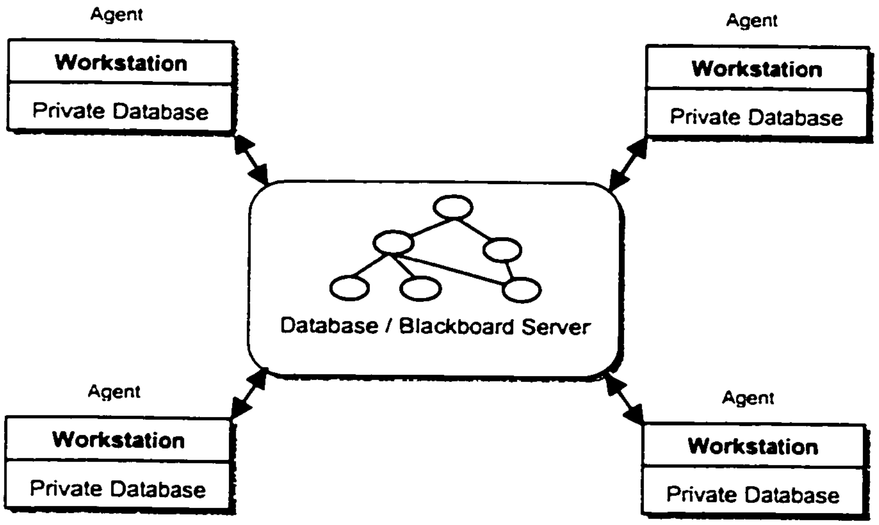


Fig. 2.14. DICE Coordination Framework (Ahmed et al. 1992).

- Peltonen et al. (1993) introduced an engineering document management system (EDMS) which can provide document approval and release procedures. The system models CAD drawings and other engineering documents as objects, which can be composed of sub-documents and have multiple versions and representations. The system, however, was not designed for distributed collaborative environments, which are more common in multi-disciplinary situations.

- Spooner and Hardwick (1993) have developed rules to coordinate concurrent changes, identifying and resolving conflicting modifications. Prasad et al. (1993) have outlined seven categories of information management needs of concurrent engineering environments: information modeling, teaming and sharing, planning and scheduling, networking and distribution, reasoning and negotiation, collaborative decision making, and organization and management. The most interesting part of this study is the detecting, managing and communicating changes within the design team, and identifying and resolving any inconsistencies among the various designs.

- In addition to capturing the design intent, Ganeshan (1992) developed a system to initiate backtracking in case of design changes. The system considers the design as a set of objectives that have their corresponding variables. It uses an expert system to perform a backtracking procedure when a variable associated with an objective is changed.

- Krishnamurthy and Law (1995) presented a change management model to support multi-disciplinary collaborative design environments. The model uses a data management model for collaborative design, which consists of three layers: versions, assemblies, and configurations. A version is a specific design description within a single discipline. Assemblies represent the aggregation of the designs in each discipline. Configurations integrate designs from each of the participating disciplines to describe an overall project. A configuration is a set of assemblies, one from each discipline along with a set of constraints that describe the set of interactions among the individual design disciplines. Despite its importance, the system is applicable only to specific design situations and did not address the capturing of design rationale, which is an essential requirement to manage design changes.

- Herman (1995) proposed a computer-based architecture called the Intelligent Design Environment for Engineering Automation (IDEEA) that integrates three distinct areas of research: team coordination, product models, and information management. He developed an architecture that integrates Artificial Intelligence technologies, engineering tools, a team coordination methodology, and an object-oriented database management system into a single framework that supports collaborative product development activities. He also developed a system for managing the modification of both data and knowledge by capturing the authorship of all information that is added during product development. As his approach may be successful in industrial and mechanical applications, it may not be suitable for the management of changes in a multi-disciplinary design process.

- Another interesting change management system was proposed by Mokhtar et al. (1998). The system includes an information model for managing design changes in a collaborative environment. The proposed information model uses a central database for projects, which is composed of the management database and the building components database. The management database contains information required to manage the various functions of the information model. The building components database, on the other hand, functions as a repository for all design data that are necessary to describe a project. The proposed system is capable of propagating design changes and tracking past changes. This system, however, did not address the problem of recording design rationale, which is an essential element in managing design changes.

It is noticed that researchers have mainly focused on representing design information and recording design rationale with limited efforts related to managing design changes. This is coupled with the lack of standards to organize design information in a structured format. There is a clear need, therefore, for an effective approach to address this crucial problem.

## 2.7 Conclusion

As a preliminary step to establishing a collaborative design environment that facilitates communication among project participants and improves coordination, an in-depth literature review was presented on several areas related to the present study including the traditional design process, design improvement programs, Internet and collaboration tools, models for representing design-information, and models for design-change management. Based on the literature review, the following conclusions could be made within each of these areas, thus forming the specifications for the developments made in this study:

1. **Traditional Design Process:**
   - A survey among design experts needs to be conducted to elicit their useful rules-of-thumb for preventing mistakes, detecting mismatches, and effectively communicating changes. The survey will also help in documenting the flow of design information among the participants involved in the design process.

2. **Design Improvement Programs:**
   - Design coordination has been identified in this study as an independent effort that focuses on the design development process and accounts for its unique difficulties and challenges

3. **Internet and Collaboration Tools:**

   - Internet has been identified as a powerful low-cost tool for communication and sharing of information. The need to develop design mechanisms based on the Internet is established.
   - Collaboration tools provide general-purpose group scheduling, database management, and file sharing and have recently added Internet capabilities. Adapting these tools to the requirements of engineering design is considered an important aspect of an Internet-based design process. Also, Internet videoconferencing, chatting, whiteboard discussions, and document-transfer can be used to provide custom solutions for design coordination and site-to-head-office communication.

4. **Models for Representing Design-Information:**

   - Building product models describe a building project with a hierarchy of relations between building objects. This type of representation is essential to store various information about the building geometry, inter-relationships among components, and the design rationale.
   - The hierarchical data representation needs to be simple and practical so as to be used in real-life. This can be done by constructing a building project hierarchy that combines the architectural, structural, mechanical, and electrical information.

5. **Design-Change Management:**

- Building project information and design rationale need to be stored into the hierarchical building product model. Recording design rationale can be done using a concept similar to the system developed by de la Garza and Alcantara (1997).
- The building project information and the design rationale need to be linked to an automated communication system to manage design changes in a collaborative environment.

# Chapter 3

# Analysis of the Traditional Design Process

## 3.1 Introduction

The quality of design has, undoubtedly, an extensive impact on all subsequent stages of a project's life cycle. To produce a quality design, effective coordination among all design participants becomes an essential requirement for success particularly within the prevailing market pressures on design firms to downsize, restructure operations, and work more productively and cost effectively. Coordination, however, has traditionally been applied through manual methods (Mooney 1995). As discussed by many researchers (Mooney 1995; Teicholz and Fischer 1994; Dubois and Parand 1993), this practice has proven to be costly and ineffective.

This chapter presents the results of a questionnaire survey conducted among twelve leading design firms in Canada. The survey elicited the manner by which expert designers prevent mistakes, detect mismatches, and effectively communicate design changes among various design teams. Based on the survey findings, common conflict areas are identified along with simple heuristic rules used by expert designers to circumvent such conflicts. Solutions to some coordination-related problems have also been presented in this chapter and areas of potential improvement to the design process identified. Accordingly, a design coordination scheme has been suggested and common inter-relationships within the design development process have been explicated. Recommendations toward a more efficient design process have been presented.

## 3.2 Questionnaire Survey

As a preliminary study, a questionnaire survey was first designed considering input (through interviews) from a number of expert designers (Hegazy et al. 1998). The survey was mailed to twelve leading Canadian design firms who have participated in a wide variety of small to large projects, including the Hibernia oil platform in Newfoundland. The questionnaire was organized into three sections: (*i*) about your firm; (*ii*) team coordination; and (*iii*) coordination among different design teams. The first section elicited general information about the participating firms, including specialty, services, average job size, number of employees, and a ranking of the most costly items in the firm's operation.

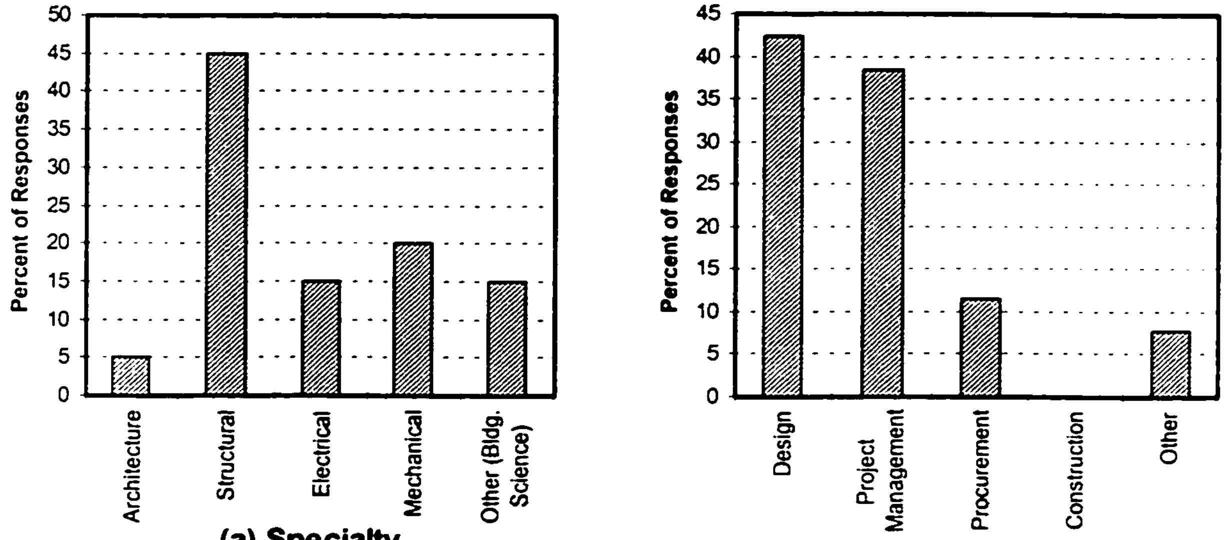
Analysis of the twelve responses received shows the profile of respondents as illustrated in Fig. 3.1. It is noted that in responding to the individual questions, some firms specified their involvement in more than one category of answer (e.g., specialized in structural as well as mechanical design) and this has been considered in calculating the "Percent of Responses" values shown in Fig. 3.1(a).

As can be derived from the figure, the participating firms can be categorized as medium- to large-sized firms engaged in a wide spectrum of project types and sizes.

### 3.2.1 Team Coordination

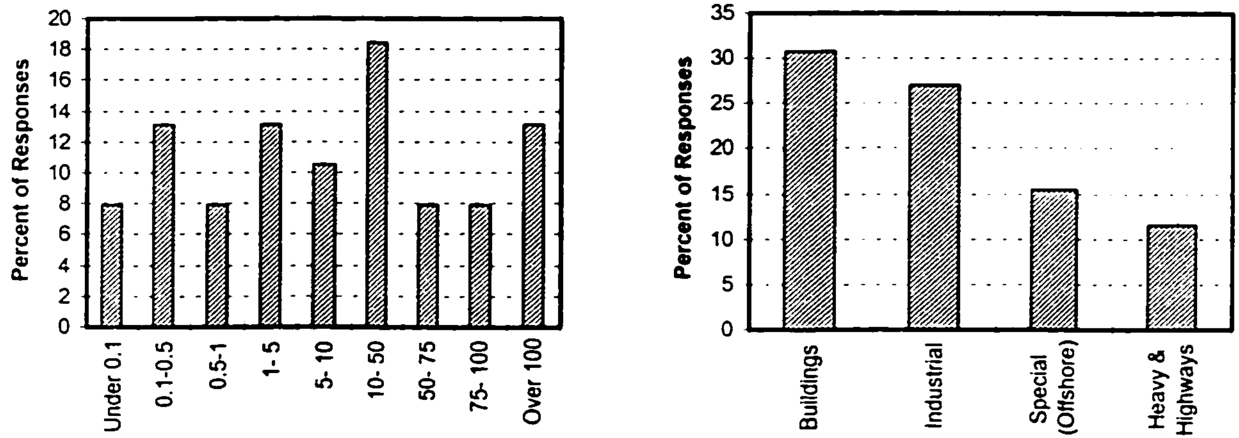
The second section of the survey focused on the internal procedures used by the participating design firms to coordinate a particular design among team members. This section also elicited some of the team-coordination problems encountered and designers' experience-based rules-of-thumb used to ensure consistency, circumvent errors, and detect problems.

From the responses received, the size and formation of a design team, as expected, were reported as job-size dependent. A typical team consists of 1 to 5 designers; 1 to 5 draftsmen; a leader (if needed); a checker (if needed); and a construction expert (if needed). The average time a team takes to produce a preliminary design ranges from 5 to 40 days, depending on job size while the average time taken to produce a detailed design is 105 days (ranging from 30 to 180 days). The tools used by the participating firms for design and drafting are shown in Fig. 3.2. These are primarily manual for design and CAD for drafting. Coordination among team members is maintained through meetings when problems arise and consultations with team leaders, as shown in Fig. 3.3.



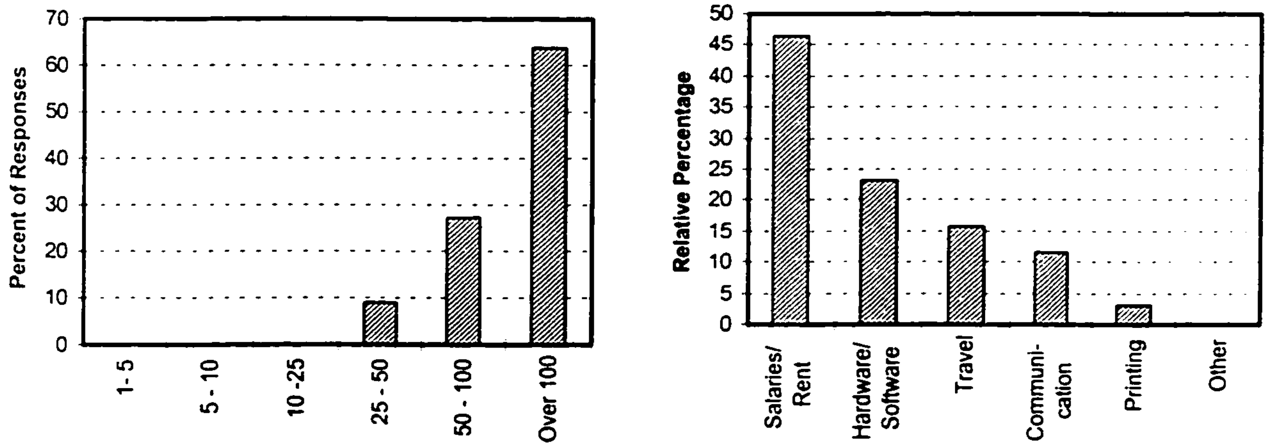
(a) Specialty

(b) Services



(c) Project Size ($ millions)

(d) Project Types



(e) Number of Employees

(f) Office Expenses

Fig. 3.1. Profile of Survey Respondents.

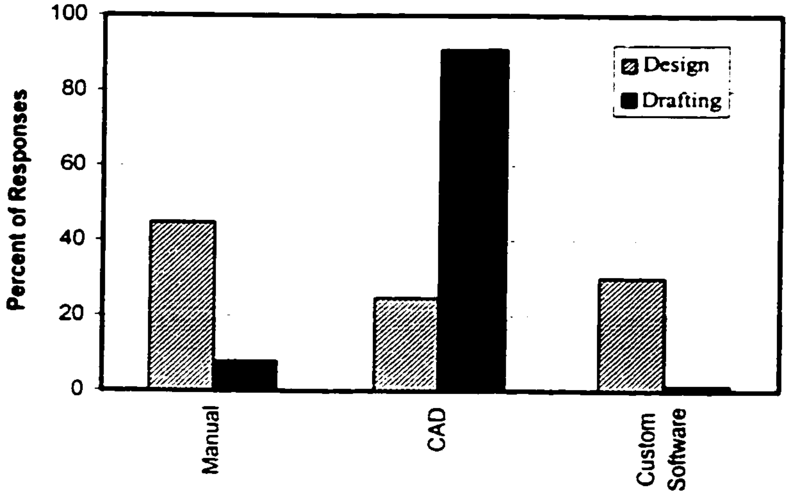
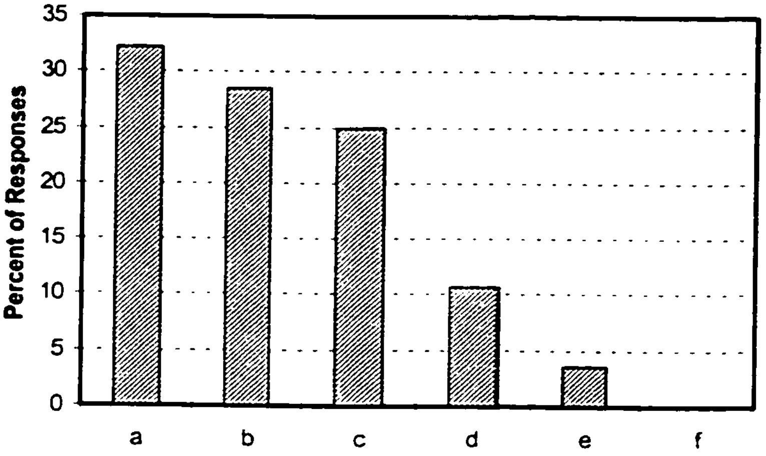


Fig. 3.2. Tools Used for Design and Drafting.



**(a)** Meeting if problem arises;
**(b)** Ad-hock, individuals consult with leader;
**(c)** Regular meeting every week;
**(d)** Meeting at preset milestones;
**(e)** Meeting after all members finish; or
**(f)** Other

Fig. 3.3. Team-Coordination Strategies.

Common situations that promote inconsistencies in design and drawings within a team are compiled in Table 3.1, along with the preventive measures suggested by the respondents. The reasons behind these problems, as can be determined from Table 3.1, are basically lack of administration of changes, errors caused by inefficient office procedures, and, to a limited extent, external factors. Also, simple tips and rules-of-thumb for preventing errors and better design coordination are presented in Table 3.2. Such tips can be used as helpful guidelines for organizing internal office procedures to ensure quality design and drawings.

**Table 3.1: Examples of Team-Coordination Problems.**

| Problem | Solution |
|---|---|
| Designers leaving project | Proper documentation of design |
| Client is vague | Ensure full understanding |
| Designer is delaying the draftsmen | Schedule the work and provide deadlines |
| Information not distributed | Ask, do not wait for others to tell you |
| Vague directives | Be direct: "Joe to send information to ...." |
| CAD drawing version not known | Specify plot date and time and the name of the draftsman on all CAD plots |
| Last minute client changes | Additional cycle of checking |
| Changes come too quickly | Must get sufficient time |
| Drafting team omitted some important details | Nominate one draftsman to be responsible for that matter |
| Tight budgets | Reduce complexity of design and reduce work hours |
| Numerous changes | Better coordination |
| Omissions | Thorough analysis |

**Table 3.2: Expert Rules-of-Thumb for Team Coordination.**

| Rule-of-Thumb or Tip | Reason |
|---|---|
| Do plan drawings before sections | Plans needed for coordination with other disciplines |
| Show dimensions once (either on plan or cross-section) | Change only once |
| Establish early where to have bracing | Design for lateral loads |
| Simple hand calculations for the main forces | Avoids big mistakes |
| Standardize the user-defined variable names | Prevents loss of information |
| Try to have staff with field experience | Find locations where things do not work |
| Weekly interface meeting | To discuss clashes and problems |
| Communicate changes in writing and follow up with a meeting | Ensures all members are working with the same information |
| Trace the load path for structural loads | This often finds a flaw in design logic |
| Look for architects' details that do not work | Looking for disparity and big errors |
| Leave all general gridline dimensions and levels on architectural drawings and off structural, mechanical, and electrical drawings | This minimizes the chance of conflicting information if only one dimension is updated |
| Check similar structural members | Looking for disparity and big errors |
| Use the design and drafting checklists | Looking for disparity and big errors |
| Catalog and use typical details | Consistence among projects |
| Try to use the same team members | Familiar and cooperative team |
| Produce each drawing to a single scale | Facilitates implementation of changes |
| Fully understand the limitations of your application software | Prevents large mistakes |
| Have master specifications with notes and highlight locations of frequent changes | Aids in not forgetting clauses and avoids inconsistencies |
| Cross check critical structural members | Avoids serious errors |

### 3.2.2 Coordination among Multidisciplinary Design Teams

The third section of the survey elicited the participants' practice in coordinating a design among the different disciplines involved in a project. It also elicited some of the multi-team coordination problems frequently encountered and designers' rules-of-thumb used to ensure consistency and proper exchange of information among teams.

Respondents provided information regarding their methods of: 1) disseminating project information; and 2) administering design changes, as two important aspects of multidisciplinary design coordination. On the one hand, disseminating design information among teams is primarily done through regular weekly or biweekly meetings, as shown in Fig. 3.4. Respondents, however, highly emphasized the importance of starting these meetings early enough in the project, coupled with information seminars to communicate project objectives, ensure full understanding, and establish an effective coordination scheme. Design information and drawings are exchanged, according to the survey, mostly (65%) using paper rather than computer files (35%). Among the disadvantages of using paper, as replied by respondents, are printing time, cost, the time needed to locate information, and "killing too many trees." While computer files were perceived as less costly and more easily communicated, issues of their acceptance as official documents were raised since they can be changed and it is sometimes cumbersome to keep track of their multiple versions.

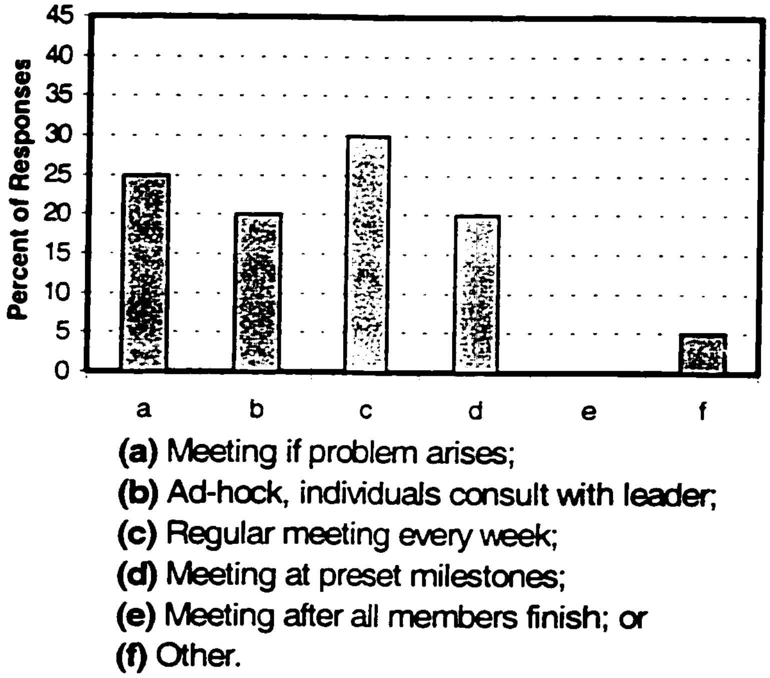


**Fig. 3.4. Coordination Among Different Teams.**

Design changes, on the other hand, are documented by the respondents in memos and "change advice notices" that are carefully filed. In this regard, some firms follow the standard specifications for quality-assurance/quality-control, such as the British Standards. Among the first things to be checked by respondents when receiving a design change is its impact on design assumptions, the scope and area of change, approval by management, clarity of information, and budgetary implications. Examples of poor multidisciplinary design coordination are compiled in Table 3.3 along with the preventive measures suggested by the respondents. Some of the tips and rules-of-thumb used for preventing errors and better coordinating design are also presented in Table 3.4.

**Table 3.3: Examples of Multi-Team Coordination Problems.**

| Problem | Solution |
|---|---|
| Delay in obtaining information | Regular meetings, phone calls, and deadlines |
| Conflict | Know what other teams want & how they work |
| Late delivery of a piece of equipment due to Mechanical team not being informed of a change in construction method | Full distribution of all the information |
| The flow of information from the owner/ contractor to the design team through different people causes misunderstandings | Single point of contact |
| Many changes in a short time period; not everyone in the team gets informed | Cross-check that each individual gets all the information on the changes |
| There will be, at times, all sorts of problems | Solution is time, communication, and after thought |
| Inadequate structural headroom or design load for Mechanical or Electrical equipment | Earlier start by mechanical and electrical teams and dialogue from all involved |
| Mechanical opening required through a structural member | Earlier start by mechanical and electrical teams and dialogue from all involved |

### 3.2.3 A Suggested Coordination Scheme

The last part of section 3 of the survey requested the participants to identify important milestones throughout their design at which they need to send or receive information to and from other teams. Based on the responses received, a coordination scheme has been compiled in Table 3.5, showing at different design stages the information to be communicated and the purpose for which it is going to be used. The suggested coordination scheme of Table 3.5 sets a general guide for design firms to follow or change according to their own environment. In setting a similar scheme, input from different participants has to be encouraged including suppliers and other third party subcontractors. Also, other factors could be considered such as design fast-tracking and contract requirements. Some respondents, for example, have indicated the possibility of starting foundation design after the 5-10% stage. This indicates the need to finalize the foundation package early enough to start construction as early as possible. In normal situations, however, foundation design is done once details of the superstructure have been finalized and accurate loads calculated. In harmony with the suggested coordination scheme, common inter-relationships among the participants throughout the design development process were schematically represented for building projects in Fig. 3.5. The level of involvement of each team is presented in the figure along with the flow of the various design

**Table 3.4: Expert Rules-of-Thumb for Multi-Team Coordination.**

| Rule-of-Thumb or Tip | Reason |
|---|---|
| Maintain unofficial contact with other teams | Find out about upcoming changes or problems |
| Use a single set of drawings for review by all teams with comments color coded | Have comments on one set of drawings, identifying who has checked what |
| Estimate what answer you expect from other teams as you design | Provides useful experience in checking designs |
| Use a third party checker | New look at work, independent viewpoint, more likely to notice missing information |
| Try to eliminate complex design details | Easy to communicate |
| Establish a specific procedure to handle different design changes | Standardize and simplify the implementation of changes |
| Communication | Silence is, among other things, the reason for many problems |
| Check important (critical) areas, give priority | Not everything has the same importance |
| Check a few columns and beams particularly critical ones | Gives benchmark for comparison and avoids serious errors |
| Ask questions and remain open to answer questions from other teams | Communication is of utmost importance on multi-team jobs |
| Distribute the information consistently to all the teams, whether or not it seems necessary | There may be impacts, which at the time of distribution, one may not be able to appreciate |
| When necessary, press other teams to complete their work to answer your team's needs | All teams work together to achieve quality design |

## Table 3.5. Flow of Information from and to Different Design Parties

| Design Stage | Information Flow | Type of Information | Use of Information |
|---|---|---|---|
| **0-5 %** | ● Architect to owner | ● Feasible conceptual designs. | ● Owner to decide on best alternative(s). |
| **5-10 %** | ● Architect to all disciplines | ● Size of project and conceptual design;<br>● Type of construction (concrete, steel,...etc.);<br>● Client requirements; and<br>● Project specific requirements. | ● Assign resources;<br>● Start preliminary studies and schematic design;<br>● Prepare out-line specifications and rough estimate; and<br>● Prepare design criteria. |
| **10-15 %** | ● Architect to surveying company<br>☐ Architect to soil investigation company<br>● Mechanical to architect<br>☐ Structural to architect | ● Site plan.<br>☐ Site plan, floor plans, and building sections.<br>● Location of shafts and the estimate of duct sizes.<br>☐ Estimated beams sizes; and<br>☐ Locations of columns and shear walls. | ● Start topographic survey on site<br>☐ Start soil investigation work on site<br>● Locate shafts on floor plans and decide on floor heights.<br>☐ Decide on floor heights; and<br>☐ Locate columns and shear walls on floor plans. |
| **15-20 %** | ● Architect to all disciplines<br>☐ Surveying company to the architect, structural, and mechanical disciplines<br>● Soil investigation company to structural | ● Floor heights and preliminary building dimensions.<br>☐ Topographic survey drawings.<br>● Preliminary soil investigation report. | ● Prepare for detailed design.<br>☐ Identify building and footing levels, site grading, and site drainage.<br>● Investigate feasible foundation types. |
| **20-40 %** | ● Architect to all disciplines<br>☐ Mechanical to electrical<br>● Mechanical to structural | ● Completed preliminary architectural drawings.<br>☐ Power requirements for mechanical equipment.<br>● Equipment locations, loads, and openings in slabs. | ● Start detailed design.<br>☐ Design power supply.<br>● Design slabs, beams, columns, and footings. |
| **40-60 %** | ● Mechanical to architect<br>☐ Mechanical to structural<br>● Structural to architect<br>☐ Electrical to architect<br>● Soil investigation company to structural | ● Final mechanical duct sizes, shafts locations, and shafts dimensions.<br>☐ Final mechanical duct sizes, shafts locations, and shafts dimensions.<br>● Final beam depths and column dimensions; and<br>● Final column and shear wall locations.<br>☐ Final electrical room dimensions.<br>● Final soil investigation report. | ● Finalize floor heights and continue on the architectural plans, sections, and details.<br>☐ Finalize beam sizes and locations of openings.<br>● Finalize floor heights and continue on the architectural plans, sections, and details.<br>☐ Continue on the plans, sections, and details.<br>● Finalize foundation design. |
| **60-80 %** | ● Architect to all disciplines | ● Revised architectural drawings with external works including any changes and/or modifications. | ● Finalize plans, sections, and details; and<br>● Start quantity surveying and specifications. |
| **80-100 %** | ● Architect to all disciplines | ● Final architectural drawings including all the details and any changes or modifications. | ● Finalize drawings;<br>● Finalize bill of quantities and priced bill of quantities;<br>● Finalize specifications; and<br>● Prepare conditions of the contract. |

**Note:** Same bullets in different columns indicate related information.

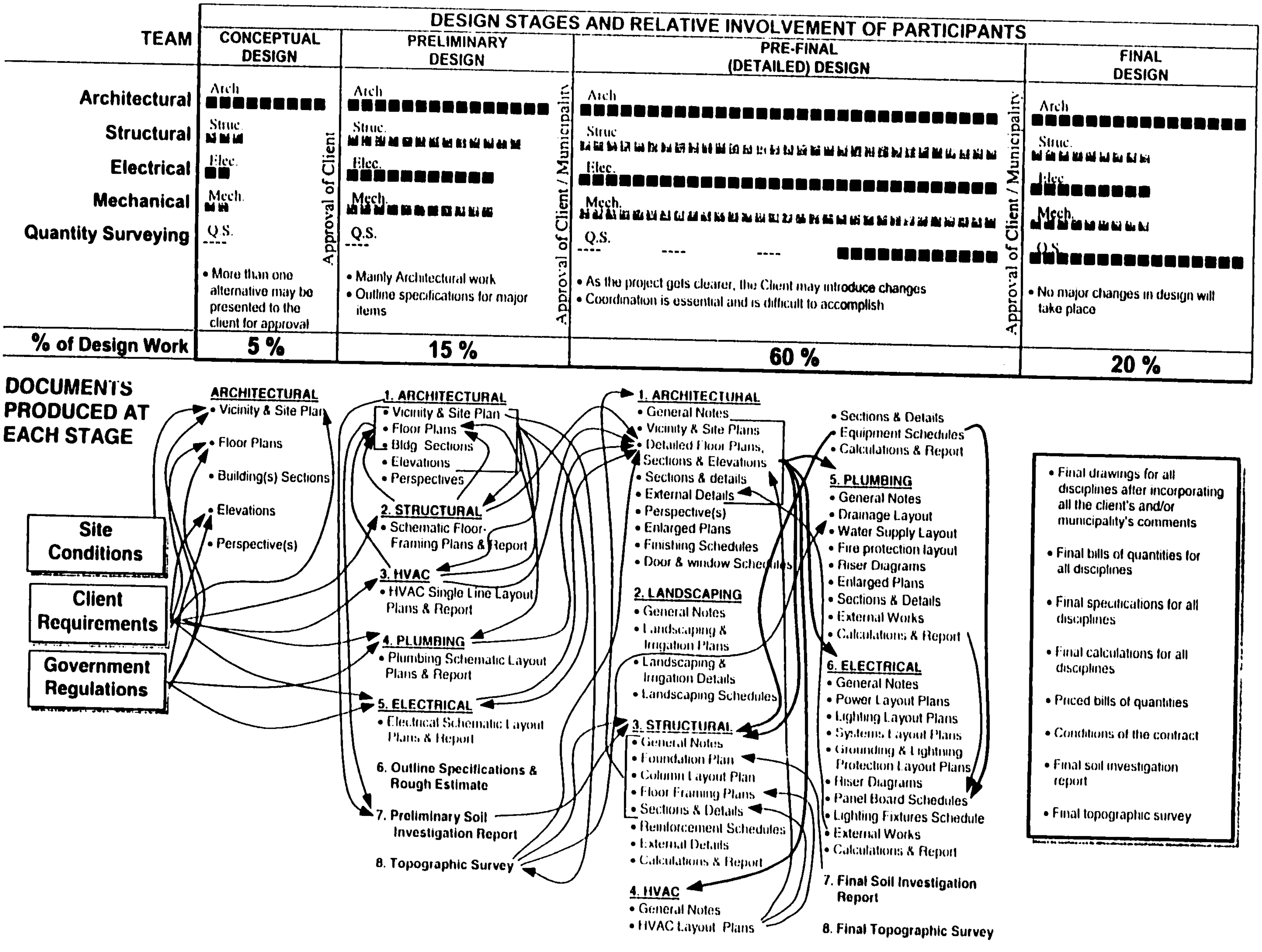


Fig. 3.5. Inter-Relationships in Design Development.

documents produced. This schematic figure can offer several benefits. It can be used to identify the parties to be communicated when a team introduces a certain change, as explained later under sections 4.2.3 and 4.2.4 of Chapter 4. The connecting arrows shown in Fig. 3.5 represent the effect of changing certain building components on other components. For example, a change in the detailed design of the HVAC equipment schedule (i.e., type of HVAC equipment) may affect the structural system and may require changes in the sizes of some slabs, beams, columns, and footings to carry the loads of the revised equipment. As shown in Fig. 3.5, this change may also affect the electrical design. As another example that can be derived from the figure, changing architectural detailed floor plans (i.e., space dimensions) may affect all other disciplines' work. It may affect the design of some structural slabs, beams, columns, and footings. This change may also affect plumbing, HVAC, and electrical designs.

The relationships shown in Fig. 3.5 can also be used as a general guide to represent the relationships among the different building components in a generic manner through object oriented formulations. Such representation helps in establishing some preliminary (default) communication paths for each building component and, accordingly, enables the development of an automated procedure for managing design changes.

## 3.3 Areas of Potential Improvement

In addition to the information presented earlier, survey respondents provided several interesting comments and criticisms to current practice that can give insight for potential improvements. One of the important issues raised is the problem associated with the large amount of paper work involved in the design process. Some of the disadvantages of using paper as the main communication media have been outlined earlier. A major obstacle to the efficient use of electronic files for communicating design information, despite recent advances, is the lack of appropriate filing systems for organizing the multitude of drawing files with their several updates and other related documents concerning specifications, changes, and other information. This is in addition to the problems of security, confidentiality, and acceptability as an official media. While there is a noticeable shift from paper-based procedures, as observed from the survey results, survey respondents have reported it as insufficient and called for more research in paperless office procedures and the use of new substitute technology for better communication, such as the Internet. The Internet (including the Internet-based tools) can, undoubtedly, have a major impact on design and can provide unsurpassed benefits to the design process, including a possible reduction in travel cost, which is the second-most costly item in office operations, after salaries and rent (Fig. 3.1.f.).

The success of a design coordination scheme is undoubtedly dependent upon effective management of not only the available resources but also the large amount of information involved. A unified system that can store design information in a structured format and manage the multidisciplinary design changes is, therefore, necessary. Based on this discussion, several developments were made in this thesis to provide an automated solution to improve design coordination. This includes the development of a system for design-information representation, design rationale storage, design-change management, and Internet connectivity.

## 3.4 Conclusion

This chapter identified design coordination as an independent program that needs to be strengthened within design firms. As a step towards enhancing the design coordination process, a questionnaire survey was conducted among twelve Canadian design firms. The survey elicited current practice related to design coordination at the inter-team level and the interdisciplinary level as well. Examples of problems and their suggested solutions were presented along with expert rules-of-thumb used by practitioners to prevent mistakes, detect mismatches, and effectively communicate design changes. Based on the survey findings, common inter-relationships were identified and can be used in identifying the parties to be communicated when a certain change is introduced and, therefore, can help in formulating proper communication paths.

# Chapter 4

# Information Model for Design Coordination

## 4.1 Introduction

The success of the design process is highly dependent upon effective aggregation of the individual designs to produce a coherent set of final design documents. In addition to its multidisciplinary nature, the design process of building projects is an evolutionary process where the designs of different disciplines must be integrated to describe the overall project. In this chapter, a practical information model is presented for storing building information, recording design rationale, and managing the multidisciplinary changes during the design of building projects (Zaneldin and Hegazy 1999, Hegazy et al. 2000). The conceptual details of the model are described in the following subsections and two examples are presented to demonstrate the concepts proposed.

## 4.2 Proposed Information Model

The proposed information model presented in this chapter attempts to improve design coordination, manage the large amount of design data, and provide a tracking mechanism for design changes. Developing the information model entails the following:

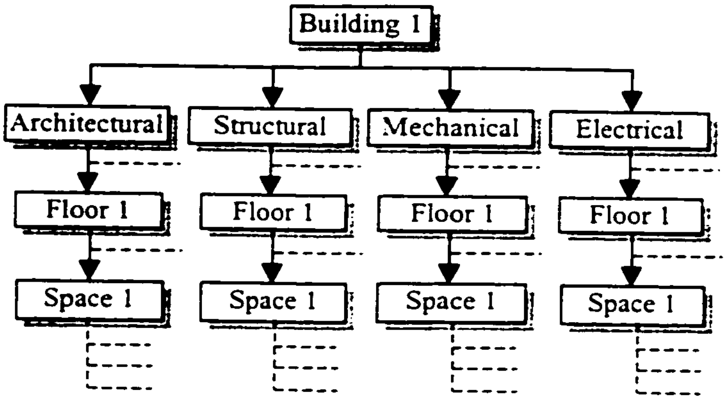
1. Establishing a building components library (BCL) that functions as a repository of design data needed to describe a building project;
2. Developing a unified information model to store the multidisciplinary design data of buildings in the form of a building project hierarchy (BPH). The components of the BPH interact with the BCL and are capable of automatically sending a change through the preset communication paths when the data of any component is changed;
3. Storing the design rationale associated with all the components of a BPH along with their performance criteria that maintains performance consistency when changes are made to any component; and
4. Developing a mechanism for keeping track of changes, following up on pending changes, and coordinating proposed changes.

The proposed information model is composed of three main parts: 1) building project hierarchy (BPH); 2) building components library (BCL); and 3) design-change management (DCM) procedures. The first part is the BPH, which stores all building data and represents this data as a hierarchy of active objects. Each object has information about its values, its documents, its design rationale, and its communication paths. The second part, the BCL, is a central repository of common building components that are needed to describe a building project hierarchy. The third part is the DCM procedures that manage the design changes made to any object in the BPH and keep track of the history of changes made by all disciplines. The developments made with respect to the model's three parts are described in the following sub-sections.

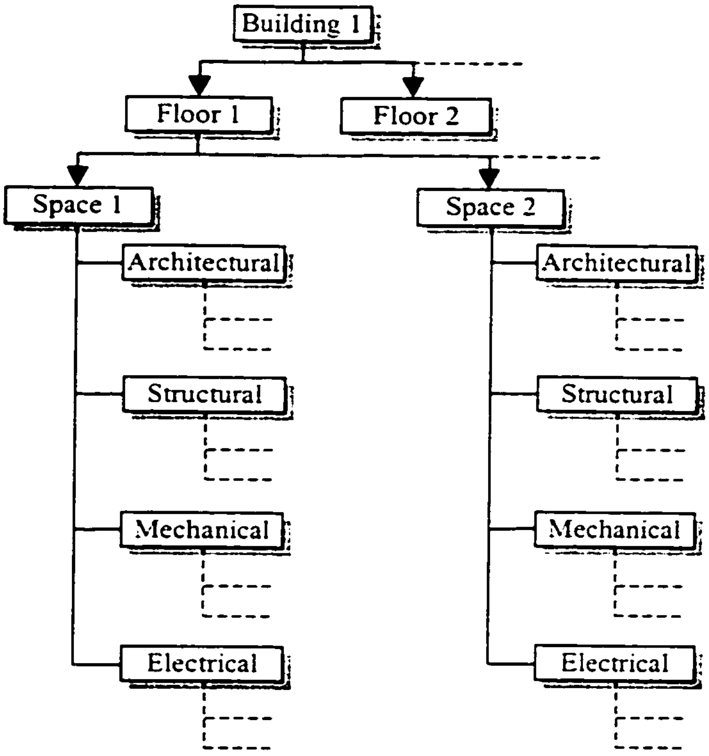
### 4.2.1 Building Project Hierarchy (BPH)

As mentioned earlier, various BPHs and building product models were developed to provide a global representation of all design information in a project. Almost all existing models represent the design systems at an upper level of the hierarchy (e.g., RATAS system of Björk (1989)). Some other models incorporate multiple BPH's for the same building. While these representations are simple and suit the work of individual design teams, they eventually separate related design information and, as such, may include conflicts in coordinating the multidisciplinary work. A certain building space, for example, has to be included four times under the four BPH branches of the architectural, structural, mechanical, and electrical systems (Fig. 4.1(a)). This may create coordination problems and is not suitable for design change management. Experimenting with this approach, it was found that the perceived coordination problem hinders the suitability of this approach to meet the objectives of this research. Therefore, a suitable representation of design information that promotes coordination and effectively manages the multidisciplinary design changes is necessary.

An alternative BPH representation is proposed in this study to unify the storage and manipulation of building data and avoid redundancy. The major criteria considered is that building components have to be represented as smart objects that contain all their multidisciplinary design information. As such, a suitable BPH would be a spatial decomposition of the building in which each space contains information related to its architectural, structural, mechanical, and electrical designs (Fig. 4.1(b)). This representation, however, imposes some difficulties perceived to occur during its implementation. One difficulty is that the same object (e.g., a certain floor space) has to be accessed by several parties designing different components within the same space. Proper multi-user access and modification rights are, therefore, essential for the unified BPH model to suit all parties. Another difficulty is that the work of each discipline will be scattered in the BPH model. Therefore, proper database design, a suitable interface, and powerful reporting are keys to the success of this BPH representation. Despite these difficulties which can be solved through proper implementation, the unified BPH representation brings substantial benefits. It encapsulates all the multidisciplinary design information into the building components with no redundancy and, as such, promotes coordination and improves quality of design. Also, the proposed BPH allows designers from all discipline to instantly view the components of all other disciplines without moving to another branch in the hierarchy. Details of the proposed BPH are shown in Fig. 4.2. It uses a combination of the aggregation/decomposition and generalization/specialization



(a) Traditional BPH



(b) Proposed BPH

Fig. 4.1. Traditional vs. Proposed Representation of Building Design Data.

hierarchies. In the aggregation/decomposition hierarchies, an entity (smallest component) can be part of an aggregation at a higher level while being decomposed into other entities at a lower level (for example, "Floor1" under the "Floor level" of "Building 1" in Fig. 4.2). On the other hand, an entity in the generalization/specialization hierarchies can be a special case of a higher level entity while being a generalization of many lower level entities (for example, the "Beam" component in Fig. 4.2 is part of the structural system of "Space 2" while containing two entities "Structural" and "Tie").

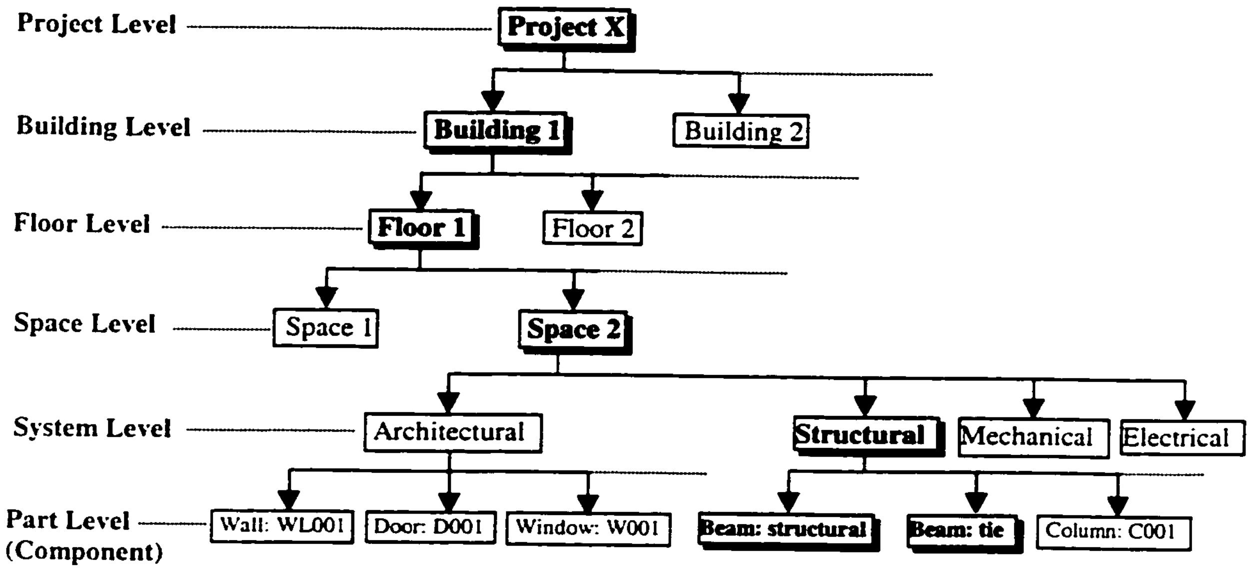


Fig. 4.2. Schematic of the Building Project Hierarchy (BPH).

As illustrated in Fig. 4.2, six levels are used in the proposed building project hierarchy: 1) Project Level: only one object with attributes that describe the site, the project size, the setbacks, etc.; 2) Building Level: can include more than one building object, with attributes that include the overall height, the type of construction, etc; 3) Floor Level: includes the different floor objects, with attributes relating to the floor level, the floor area, the floor clear height, etc; 4) Space Level: incorporates objects that correspond to all the spaces within the floor; 5) System Level: encompassing four main objects for the architectural, structural, mechanical, and electrical systems within the space; and 6) Part Level: includes the majority of the detailed building objects, such as walls, doors, windows, beams, columns, etc. A beam component, for example, can have attributes like width, depth, material, reinforcement, code-restrictions, and location-in-wall. The proposed building project hierarchy, as such, provides a unique description for each component in a building project.

### 4.2.2 Building Components Library (BCL)

The BCL serves as a central repository of all building components that are needed to create a complete BPH. The library includes active components (small trees) from the six levels described in the BPH. Individual components from all levels are stored in the library along with their attributes. Since changes to these attributes mean changes to the design that need to be easily monitored, the attributes of any component are represented as visible objects in the vertical tree of the component (Fig. 4.3). The "Space" component of Fig. 4.3, for example, has general attributes that correspond to its width, length, clear height, floor-finish-thickness, floor-finish-material, and floor-finish-color. All these attributes are represented as general objects added to the four main objects that represent the architectural, structural, mechanical, and electrical systems of the space (Fig. 4.3).

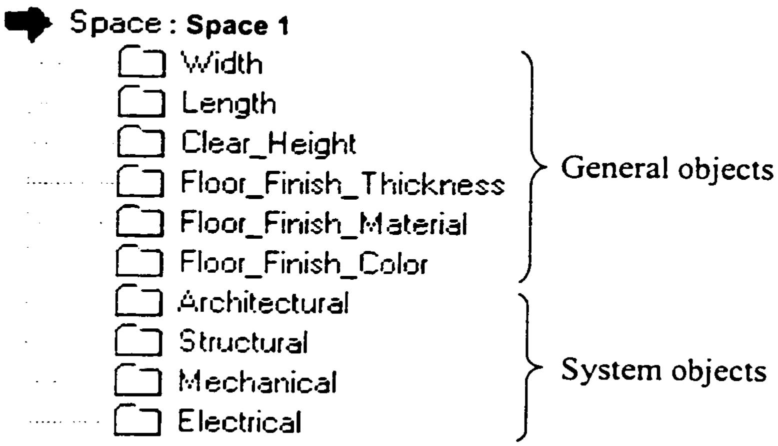


**Fig. 4.3. An Example of the "Space" Component in the Building Components Library (BCL).**

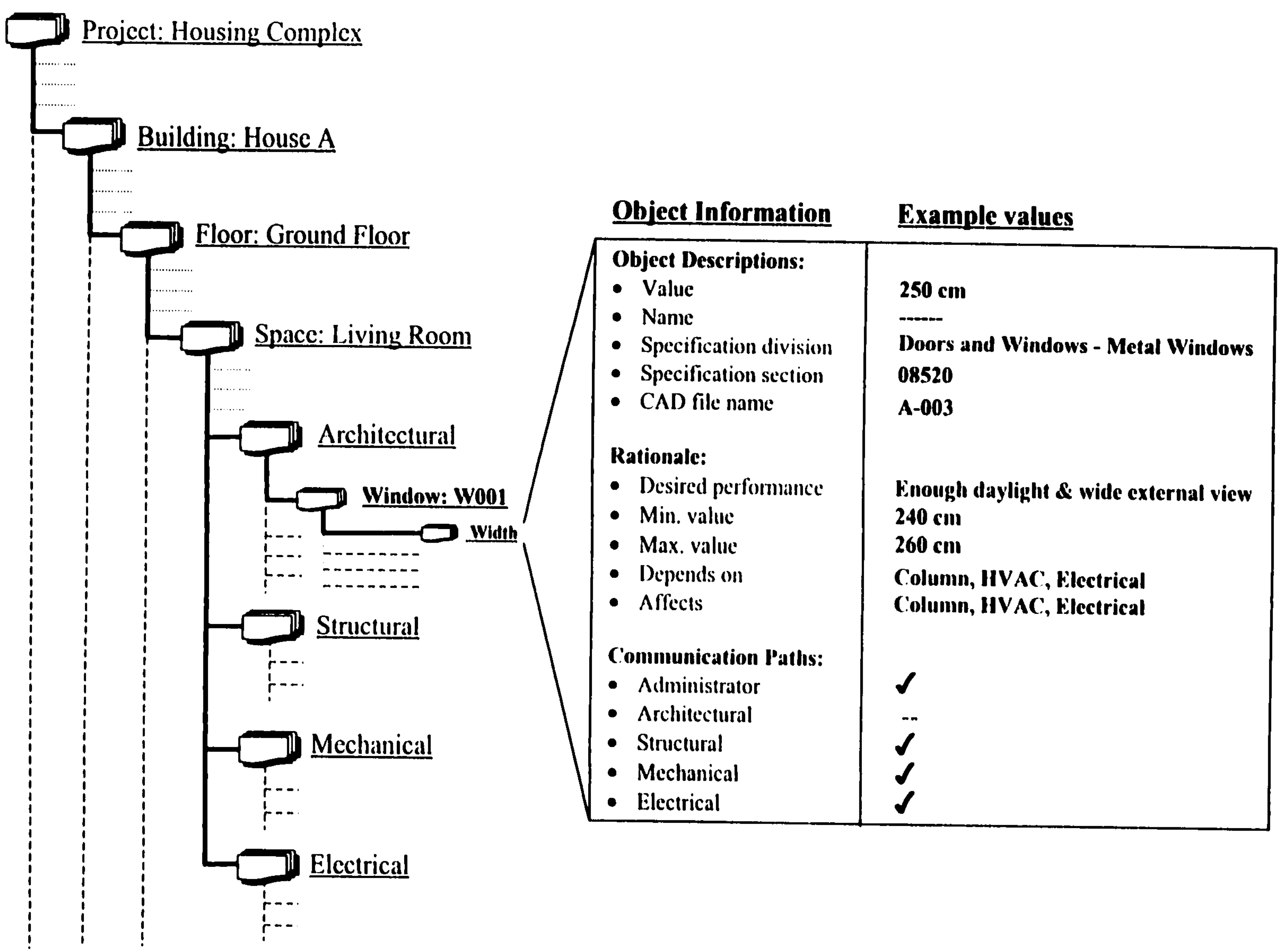
Similarly, components at a higher level include some general attributes, in addition to the attributes of subsequent levels. A "Floor" component, for example, includes general attributes related to its finish-thickness and clear-height, in addition to the spaces within the floor. Individual components stored in the BCL are used by the designer when building a BPH for a certain project. When the designer adds any component from the BCL to the BPH, its default tree is directly attached to the BPH, thus saving the designer's time and effort. To facilitate the use of BCL components, default information related to components from every discipline can be pre-identified and stored before putting BCL to actual use. To manage the different components, a reference to its discipline may be used. A structural component such as a beam or a column, for example, can have an "S" reference so that it can be accessed only by structural designers.

### 4.2.3 Object Information

The representation of building components and their attributes as objects in BCL and BPH trees is a powerful feature of the proposed information model. Each object is aware of its data and incorporates three types of information (Fig. 4.4) related to: object description, design rationale, and communication paths. These information can be numeric, textual, or can have links to external textual and geometric documents (e.g., specifications and CAD drawings, respectively).

Fig. 4.4 shows an example of the "Width" object that represents a dimensional attribute of the "Window (W001)" component. This window is a part in the "Architectural" system of the "Living room" space, which is one of the spaces in the "Ground" floor of the "House" project. As shown in Fig. 4.4, the object description of the window-width includes information related to its value (250 cm), specification division (Doors and Windows-Metal Windows), specification section (08520), and CAD file name (Drawing A-003).

It is assumed that the architect designed this window with a large area (120 cm X 250 cm) in order to provide enough daylight and wide external view to the living room. The architect's reasoning behind providing the large width of 250 cm for the window needs to be recorded to facilitate future access to this information in case the width is changed. The design rationale is represented by four information items that are recorded for each component, as illustrated in Fig. 4.4: 1) a description of desired performance criteria; 2) minimum and maximum performance values; 3) a list of components that affect current component; and 4) a list of components that are affected by changes in current component. In the example data given in Fig. 4.4, minimum and maximum values for the window width are specified as 240 cm and 260 cm, respectively to meet desirable daylight and wide external view criteria. The information in the design rationale can, therefore, be used to select comparable components from materials and equipment catalogs if changes have to take place. Also, the third and fourth data items represent important dependency relationships with other components, similar to predecessor and successor relationships in network analysis. These relationships can help in following up on the ripple effect of changes from one component to the other, according to the specified logic. As shown in Fig. 4.4, structural columns, electrical, and HVAC are affected by changing the window width and can affect the window width when they are changed. The figure also shows that structural, mechanical, and electrical teams, among others, need to be communicated when the window width is changed.


Building Project Hierarchy (BPH)

| Object Information | Example values |
|---|---|
| **Object Descriptions:** | |
| • Value | **250 cm** |
| • Name | **------** |
| • Specification division | **Doors and Windows - Metal Windows** |
| • Specification section | **08520** |
| • CAD file name | **A-003** |
| **Rationale:** | |
| • Desired performance | **Enough daylight & wide external view** |
| • Min. value | **240 cm** |
| • Max. value | **260 cm** |
| • Depends on | **Column, HVAC, Electrical** |
| • Affects | **Column, HVAC, Electrical** |
| **Communication Paths:** | |
| • Administrator | ✓ |
| • Architectural | -- |
| • Structural | ✓ |
| • Mechanical | ✓ |
| • Electrical | ✓ |

**Fig. 4.4. Object Information and its Use in the BCL and BPH Trees.**

In addition to the object description information and the design rationale information, each object in the BCL and BPH trees stores information related to the parties that should be communicated when the object data is changed by the designer. The window-width object in Fig. 4.4, for example, has preset communication paths to the administrator and to the structural, mechanical, and electrical disciplines. Any changes to the width value, therefore, will be communicated to those parties. Information related to the appropriate communication paths of various components should be decided early enough in the project and possibly stored in the BCL components before building the project's BPH. In the present study, the communication paths related to various building components have been identified based on the results of the questionnaire survey presented in Chapter 3.

### 4.2.4 Design-Change Management (DCM)

The management of changes is crucial since changes made in one discipline normally impact the design descriptions of other disciplines. In some cases, the designer who initiated the change may forget to propagate the change, may think it is insignificant, or may even assume that other disciplines are not affected by the change. To allow for efficient management of design changes, building components in the BPH need to be active and automatically report changes made to their own values. This can be done through component-related procedures for monitoring new and old values, proposing a change, sending the changes made to the component, and finding changes related to the component (Fig. 4.5). In addition to component-related procedures, other general procedures are needed for three main functions, as shown in Fig. 4.5: 1) warn design participants with the proposed changes and the approved change-proposals; 2) allow designers to respond to proposed changes and implement approved change-proposals; and 3) provide several reports that can be viewed by all disciplines such as a list of the history of all changes made throughout the evolution of the design, a list of pending changes, changes affecting a certain design party, and changes initiated by a certain design party. These reports are important particularly to the design administrator who can use them to track all changes made to a BPH and follow up pending changes on daily basis.

| | **General procedures:** | **Component-related procedures:** | |
|---|---|---|---|
| Warning | • Track proposed changes<br>• Track approved change proposals | • Propose a change<br>• Send a change<br>• Find changes history | Active components |
| Response | • Respond to proposed changes<br>• Implement approved change proposals | | |
| Reporting | • Query by affected party<br>• Query by party initiated the change<br>• List pending changes<br>• List history of changes | | |

**Fig. 4.5. Design-Change Management Procedures.**

Throughout the detailed design, it is always recommended to inform other disciplines with an intended change to any building component, before actually implementing that change. In the proposed model, therefore, if a change to any component in the BPH is necessary, a proposal of this change should be first sent to all other disciplines for approval. Introducing a design-change, however, requires the designer's full understanding of the rationale behind the original design. It helps in preventing any violation to the requirements or constraints used in the original design. The default design rationale is, therefore, sent to all other disciplines along with the change proposal. Accordingly, designers from all disciplines receive proposals for changes from other disciplines. After receiving a proposed change, other disciplines can either approve or disapprove it. Once a response is made, it will be sent to the discipline who proposed the change. Once an approval to the proposed change is received from all other disciplines, the design team who proposed the change can then implement it to the associated BPH component.

When a change is implemented, its data is recorded, including a detailed explanation of the change, its date, dates of approvals, and a reference number for the change proposal. An alarm system for tracking changes is necessary for following up on changes. Any affected party should provide a date in which they expect to implement that change. If the date is not provided, they will automatically and continuously receive messages to remind them to do so until an implementation date is provided. Similarly, if the change is not implemented on time, designers will continuously receive messages until the change is implemented. Also, in an efficient change management system, an efficient search and reporting system is necessary. All design teams can access the history of changes to monitor the changes they made, check changes affecting them, and view the history of all changes made by all disciplines.

### 4.2.5 Model Integration

The relationships among the three basic parts composing the proposed information model are shown in Fig. 4.6. When the BCL is filled with default components, a complete BPH for a new project can be generated by the architect/administrator with little time and effort using the default components that can be modified with project-specific information. All design teams work on the same BPH and, therefore, can view the designs of each other while working in their part of the BPH. This is important to avoid any coordination problems that may arise if each design team works separately. The "Space" level of the BPH includes objects for the "Structural", "Mechanical", and "Electrical" work related to that space. As mentioned earlier, controlling the access of the different design teams to the same BPH space is a problem that requires special attention. The solution lies in proper database design and special manipulation of BPH objects. The BPH data need to be stored in four separate databases for the architectural, structural, mechanical, and electrical data. Effectively, administering the access of all design disciplines to the project's BPH is an important task. Each discipline should be able to work in its BPH in full security and without interfering with other disciplines' work. To achieve this level of security, each discipline saves its own design data only. The four databases are to be put in a central repository. All parties can activate and view the project's BPH but the structural, mechanical,

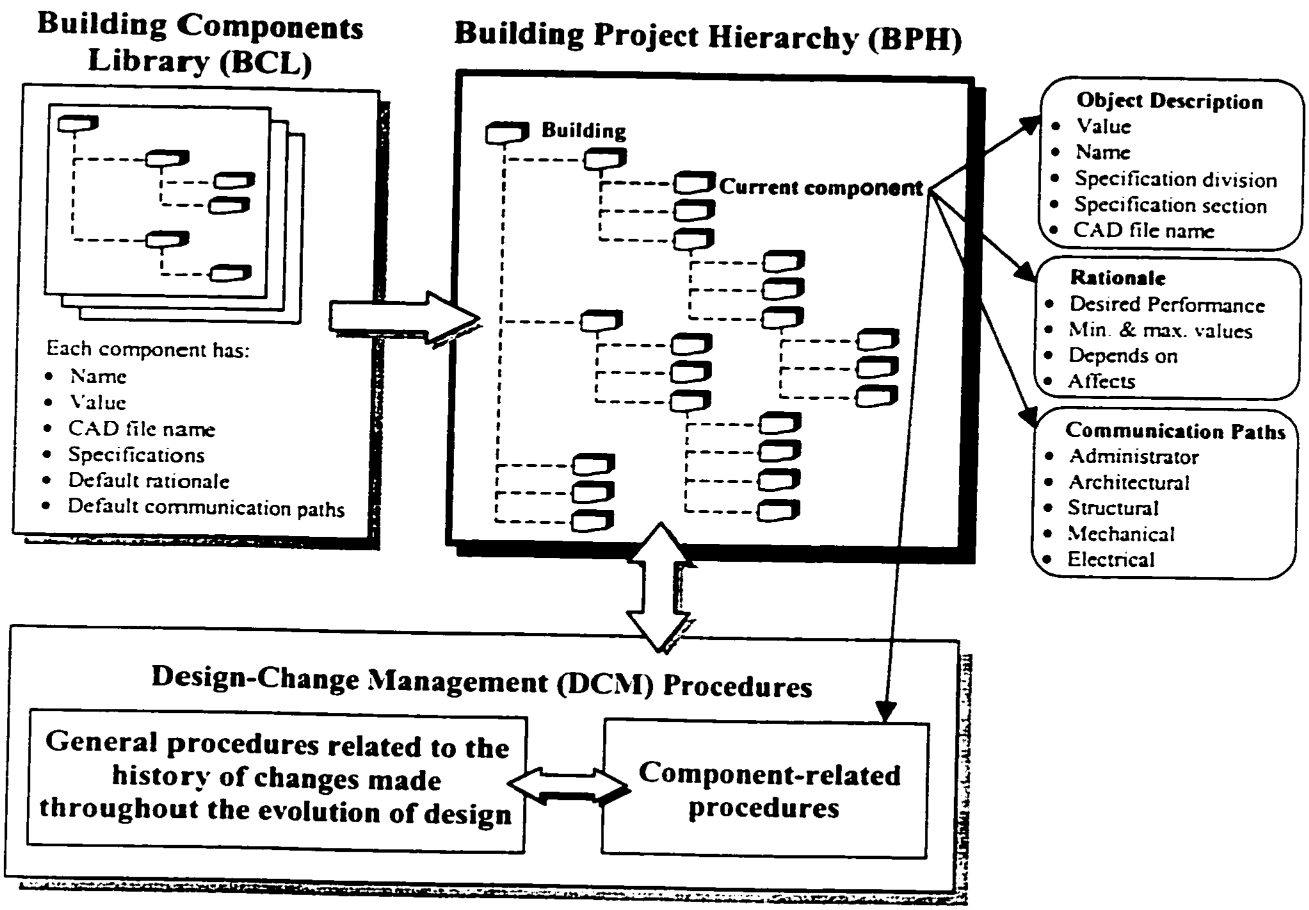


Fig. 4.6. Relations Among the Basic Parts of the Proposed Information Model.

and electrical designers can only access and work on their related components that appear under the space level (Fig. 4.7). Access of any party to its own database gives full modify/use control while access to other party's database gives view-only control.

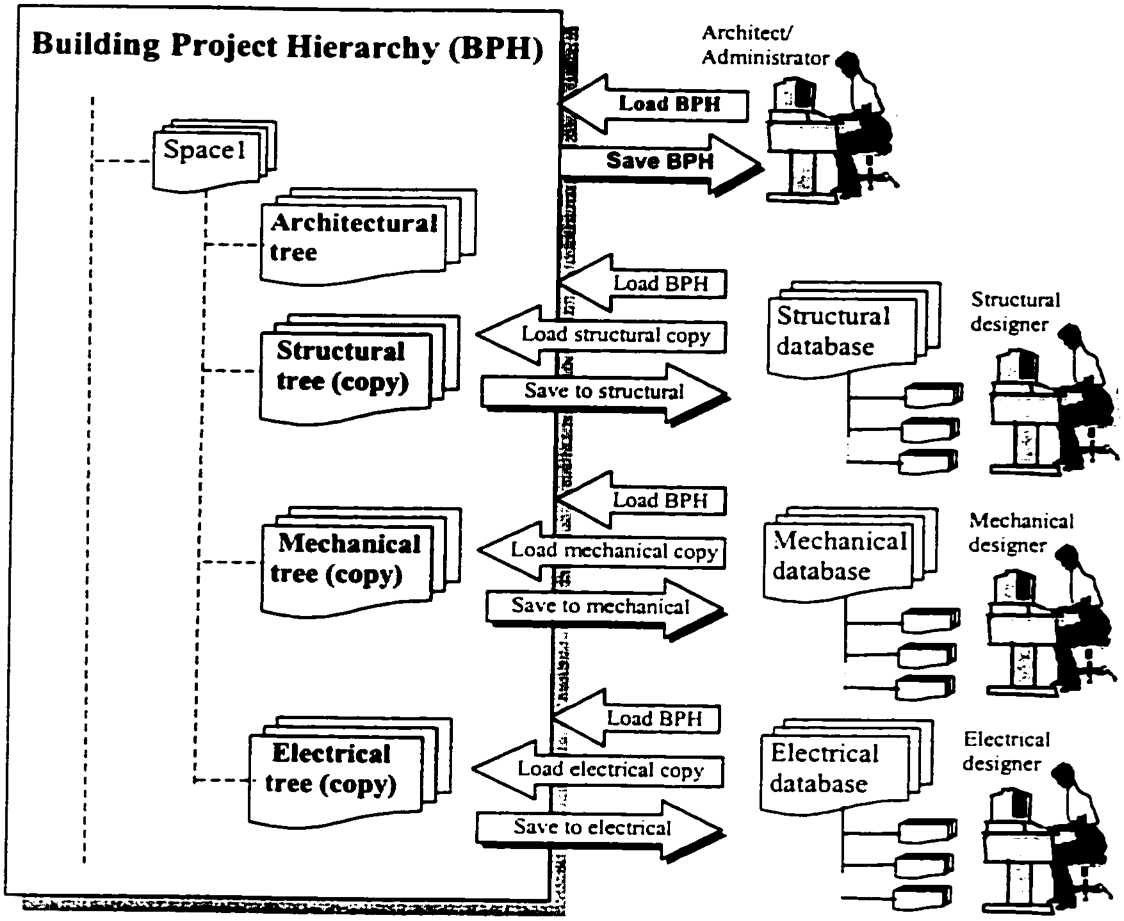


Fig. 4.7. Multidisciplinary Building Project Hierarchy.

To allow flexibility in accepting or rejecting changes to the BPH, all disciplines work on a copy of their previously saved BPH databases, and at any time they can save their work to the original databases (Fig. 4.7). This allows easy discard of any undesired modifications to the BPH and avoids continuous communication to the databases. It is noted here that the structural work, for example, while being scattered in different places in the BPH, is saved in a single structural database. This single structural database for the project contains various tables, each corresponding to a BPH space, with a reference code between the table name and its associated BPH object. Similarly, mechanical and electrical works are saved in separate databases with the design of each space saved in a separate table. More details on the implementation of the databases are provided in Chapter 5.

### 4.2.6 The Role of the Design Administrator

The proposed design coordination model imposes little changes to the traditional design process. One aspect is the introduction of a new participant in the process, the design administrator, who is highly recommended to be considered by design firms, particularly in large projects. It is noted that in some situations, particularly when the project size is small, the architect can himself assume the role of the administrator. The design administrator works as a dedicated design coordination official with the following responsibilities:

1) Generate and administer the BCL to make sure that it includes necessary building components. While the administrator have full access rights to the BCL, all other engineers can only add BCL components to their BPHs;
2) Preset the required communication paths for each component in the BCL;
3) Provide his input to the initial design rationale of BCL components, such as the dependency relationships among components;

4) Coordinate with the architect to build the initial BPH of a project, including floors, spaces, systems, and architectural components;
5) Coordinate with other designers to provide his input and solve coordination-related problems;
6) Make sure that the initial values of components in the BPH are provided within the default allowable values.
7) Track and follow up on all communications among all parties, administer pending changes, and track change proposals; and
8) Conduct regular meetings to discuss designers' comments on proposed changes, review pending changes, and monitor work progress.

## 4.3 Examples

Two hypothetical examples are presented in this chapter to illustrate the proposed concepts and demonstrate the importance of the model's three components (BPH, BCL, and DCM) to improving design coordination. The first example is a two-floor concrete building. The first floor of this building includes three offices, a conference room, two corridors, and a toilet. Each of these spaces consists of different components such as walls, windows, doors, slabs, beams, columns, etc. At an early stage of the detailed design, some architectural and structural details are shown in Fig. 4.8 and Fig.4.9, respectively. The architect was initially satisfied with the dimensions of the conference room and designed two windows (W03, and W04) to provide sufficient daylight for the room. The structural engineer, on the other hand, designed the building using solid concrete slabs supported by concrete beams and columns. This structural design was acceptable to the architect since all columns and beams will be flush with the walls and, thus, will serve the architectural needs. It is assumed also that the mechanical and electrical designers have designed some of their components for this building.

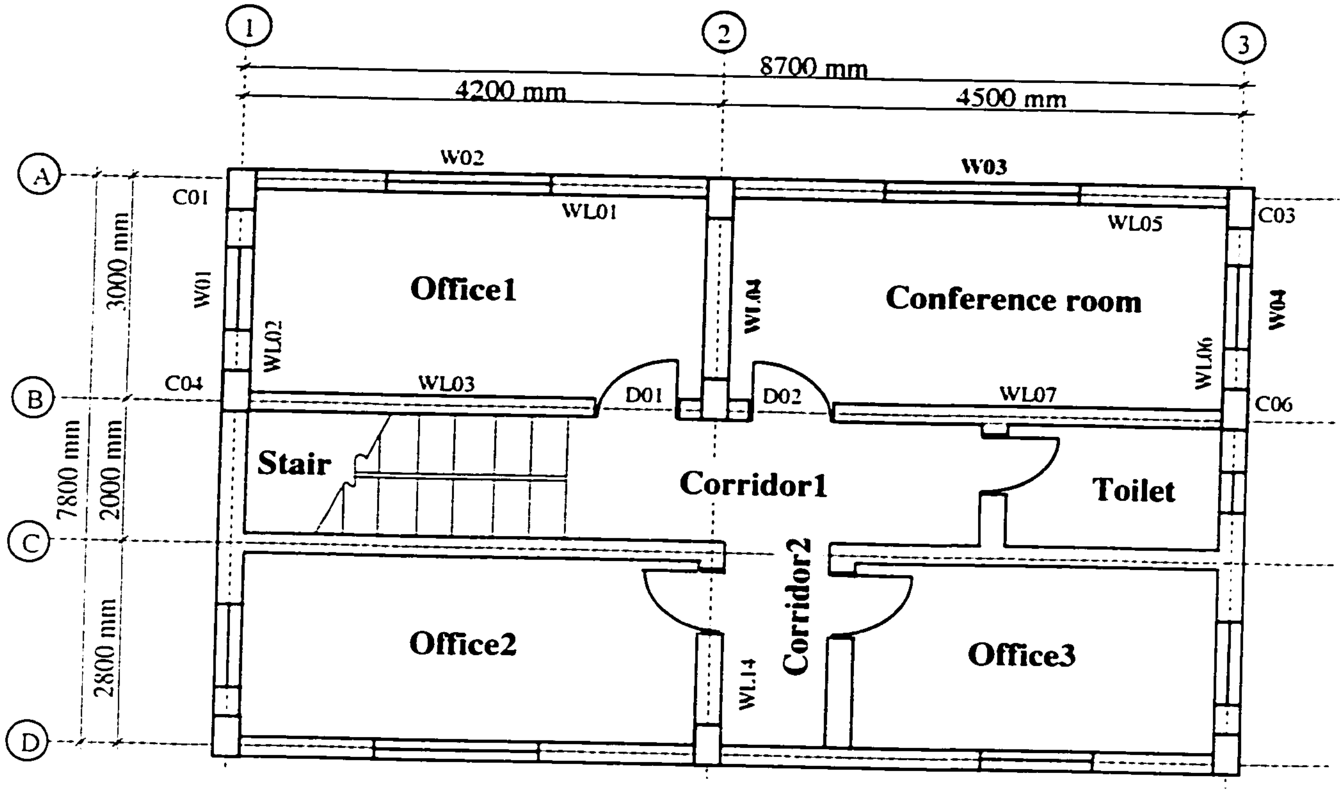


Fig. 4.8. Architectural First Floor Plan for the Concrete Building Example.

One simple change is introduced to the design at this stage in which the architect has decided to slightly change some dimensions in the first floor and enlarge the conference room by only 20 cm. With this small change, a lot of communications

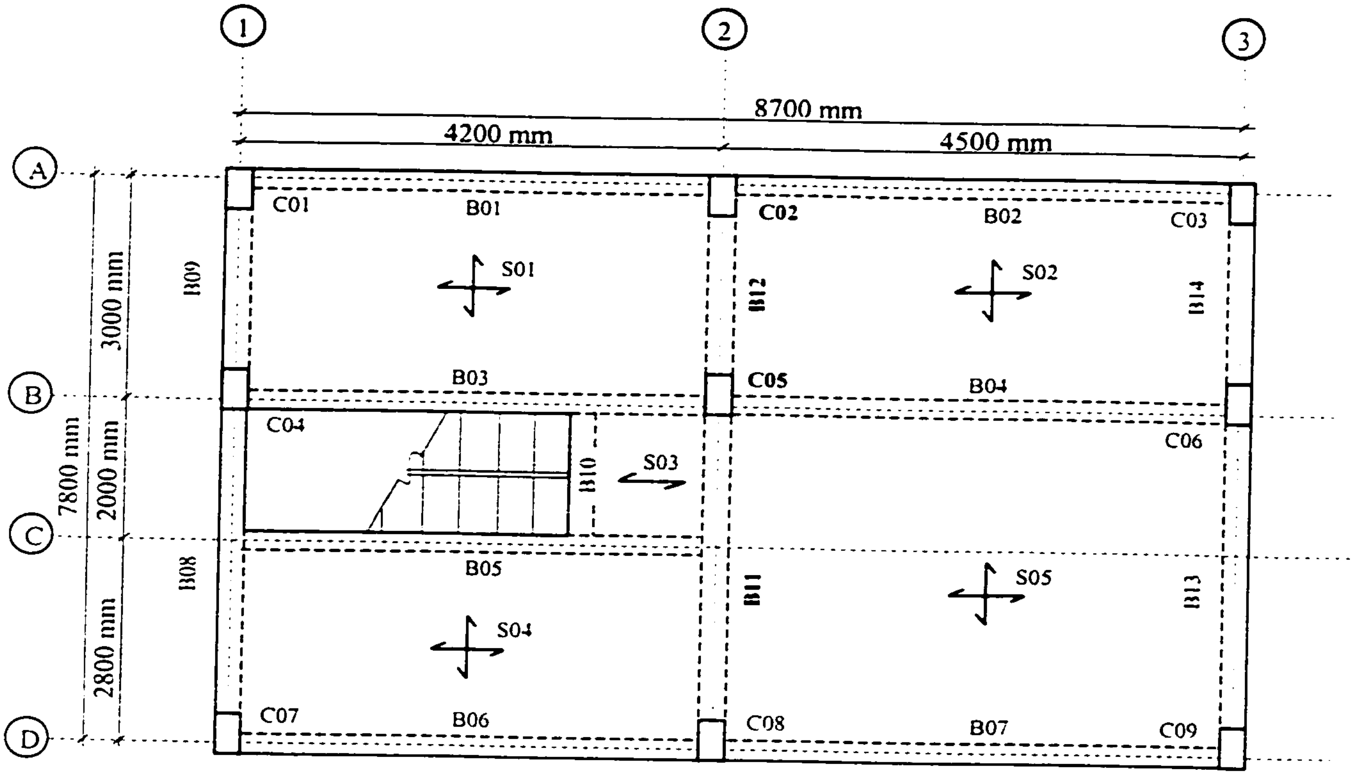


Fig. 4.9. Structural First Floor Plan for the Concrete Building Example.

among design teams have to take place. The structural engineer, for example, may propose various solutions such as those shown in Fig. 4.10. The partition wall solution shown in Fig. 10(a) most likely will not appeal to the architect since the columns and beams are not moved from their original positions and, thus, will appear in the conference room. The second solution of shifting columns C02 and C05 and beam B12 that supports wall (WL04) by 20 cm may appeal to the architect, however, will change the structural system of beams B11 and B12 from being continuous to being simply supported. This solution, however, may not be approved by the architect, since some structural members will show in the ground floor, which is unacceptable to the architect. The third solution of rotating columns C02 and C05 and shifting beam B12 by 20 cm is the preferred option to the architect. This solution, however, will require a major redesign effort from the structural engineer considering the change in the loading on some columns and the change in some beams structural system. In addition to that, the changes to the space will require architectural redesign of the windows in the conference room and office1 to maintain the desired daylight criteria. The mechanical and electrical designers will also be affected and they will be required to check the HVAC design and lighting design for the conference room and office1.

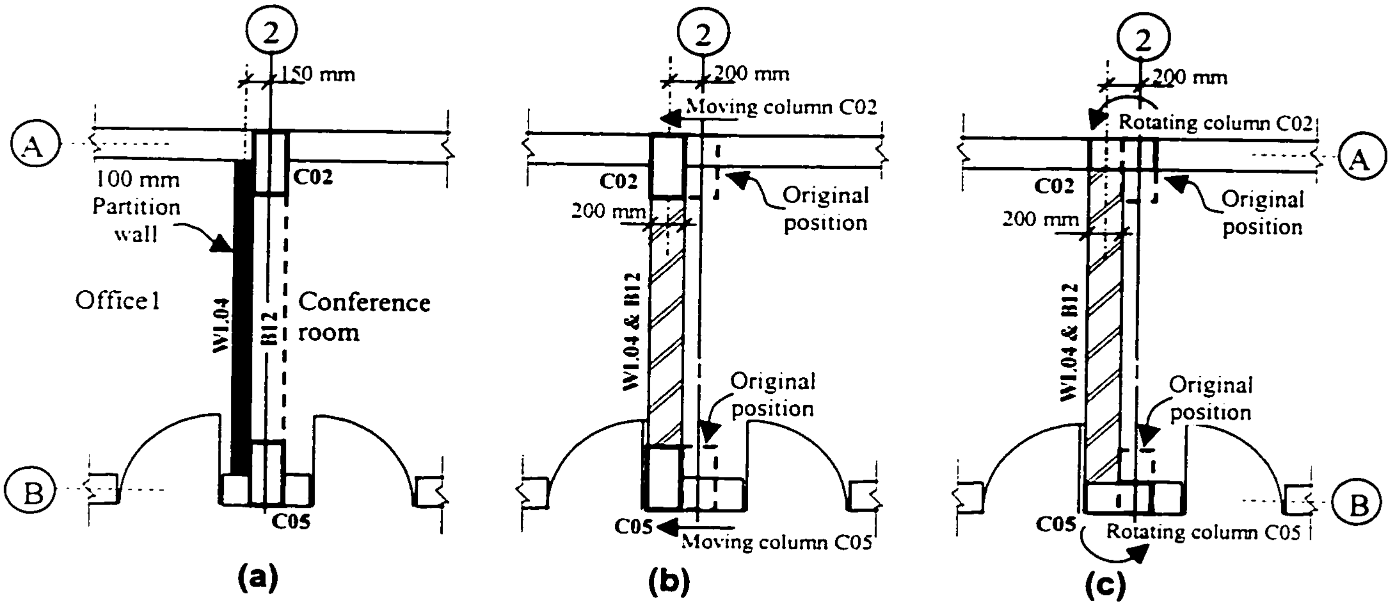


Fig. 4.10. Solutions to the Proposed Architectural Change in the Example.

Many communication problems can arise before and during the negotiation for and implementation of one of the proposed solutions, and the proposed model can help in reducing them. First, the model creates a global storage of the multidisciplinary designs that is incorporated in the BPH of the project. This will facilitate the access of any discipline to the designs of other disciplines for reference. A partial BPH for this example is shown in Fig. 4.11 with architectural and structural components specified for the conference room and office1 spaces of the first floor. The BPH can be generated easily using default components from the BCL. With BPH objects being active, they will be able to automatically communicate changes in their values to the preset communication paths, which will, in turn, notify all parties that are affected with the change. Changing the width of column (C02) in the BPH, for example, will automatically send the new values to affected disciplines. Also, storing the design rationale for the windows will enable the architect to check the desired performance criteria to make sure that any changes to window (W03) are consistent with the design rationale. In addition, design change management procedures are very important to get approvals of proposed changes, make sure that designers respond to changes, and implement approved changes.

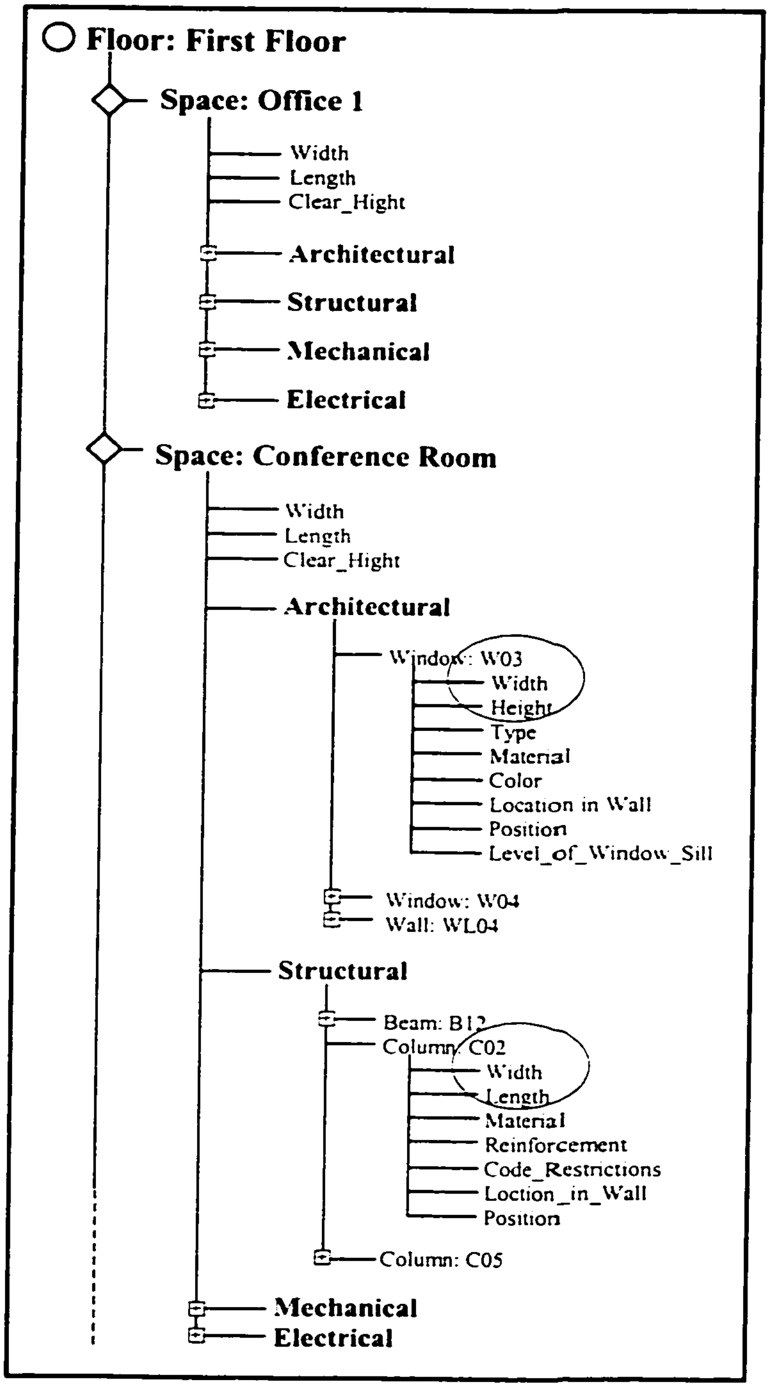


Fig. 4.11. A Partial BPH for the Concrete Building Example.

The second example is a single floor concrete house. The house is composed of a living room, a kitchen, a dining room, a bathroom, a corridor, and a bedroom (Fig. 4.12). The architect initially designed the dining room windows (W01) and (W02) to provide sufficient daylight for the room. Similar to the first example, the structural engineer designed the structural system of the house using solid concrete slabs supported by concrete beams and columns and the mechanical and electrical designers have also designed some of their components (not shown in the figure).

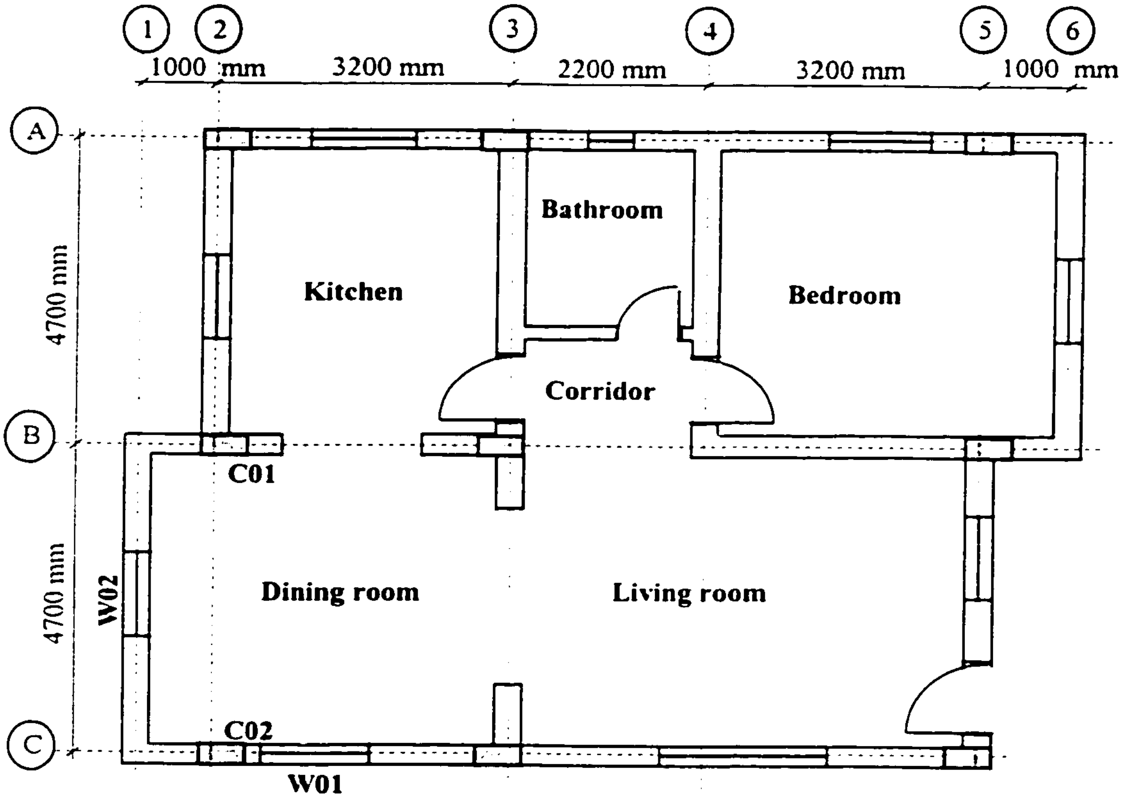


Fig. 4.12. Ground Floor Plan for the House Example.

At this stage of the design, the architect decided to change the width of the dining room window (W01) and enlarge it from 120 cm to 200 cm to provide a wider external view. With this change, the structural engineer, for example, may shift columns C01 and C02 and change the structural design of beams along axes "B" and "C", as their span lengths are changed. This is in addition to the change in the loading on some columns and footings. Also, for the dining room, the mechanical and electrical designers will be required to check their HVAC design and lighting design, respectively.

In this example also, the proposed model can help in reducing many of the communication problems. It will first create a complete BPH for the project to facilitate the access of any discipline to the designs of other disciplines. Also, by changing the width of window (W01), the width, as an active object, will automatically send the new values to affected disciplines. In addition, the proposed procedures of managing changes are essential to get approval of proposed changes, make sure that designers respond to changes, and implement approved changes. These procedures will increase the level of coordination among design disciplines to help maintain project information as current as possible. The reporting system of the present model is also important to help the design administrator follow up on pending changes and track the history of all changes made to the project.

The data of the two examples reflects a common situation in the traditional design process in which the architect may consider the increase in the room length or in the window width as insignificant and, thus, proceed with the change without informing other disciplines. As explained, this causes serious problems particularly to the structural engineer, in this case, due to the effect of these changes on his design and calculations. In more complex projects, a change by a design discipline may equally affect all other disciplines and, therefore, needs to be properly communicated and administered.

## 4.4 CONCLUSION

In a multidisciplinary environment such as the design process of building projects, vast amounts of information are exchanged among the different disciplines. In order to efficiently utilize these information, they need to be properly presented. In this environment also, changes are eminent and need to be properly managed. Managing these changes is a key point in controlling the project and insuring a consistent and well-coordinated design. This chapter presented an information model to store design information, record design rationale, and manage design changes. The proposed model uses a central BCL that is used to create a complete BPH for any project. The novel aspect of the proposed BPH is its representation of the multidisciplinary design data within each building space. In addition, each building component in the model has its preset communication paths that help in automatically communicating changes made to any component to all affected parties. Each component also allows the designer to store related design rationale and desired performance criteria. The role of the design administrator in this model is emphasized as a central coordinator. The model helps the design administrator keep track of changes, follow up on pending changes, and coordinate proposed and applied changes. The use of the information model has been demonstrated via two examples. More details on implementing this model within a collaborative environment for design coordination has been presented in Chapter 5.

# Chapter 5

# Collaborative Design System: A Prototype

## 5.1 Introduction

Undoubtedly, the quality of design has an extensive impact on all subsequent stages of a project's life cycle. Traditionally, designers are using manual procedures to communicate design changes and information. With the increased complexity and tight budgets of today's projects and the frequently introduced changes during the design process, this practice leads to inefficiencies in the design and thus affects the overall quality of the construction. This is because poorly communicated changes in design may lead to inconsistencies and, therefore, modifications become costly and difficult to manage. The resultant of these situations is delays and poor constructability of projects. The main reason behind these problems is the lack of a unified model for organizing design information and storing its rationale (presented in Chapter 4), in addition to the lack of an environment through which designers, including remote ones, can interact, share information, and automatically communicate changes in a collaborative manner.

This chapter presents the development of a collaborative system for design coordination and effective management of design changes in building projects. The collaborative system utilizes recent advances in information technology and computer collaboration tools in order to improve coordination and increase productivity in the design of building projects. Based on the structured information model presented in Chapter 4, a collaborative design system has been developed incorporating: (1) a client-server environment for representing building data, recording design rationale, and effectively managing design changes; and (2) Internet-based collaboration tools for sharing documents, reviewing changes, and conferencing among remote design participants (Zaneldin and Hegazy 1999, Zaneldin et al. 2000). Implementation issues are discussed and an example application is worked on the developed prototype to demonstrate its applicability and features. Comments are then made on the perceived changes that the system imposes on the traditional design process. The developments made provide guidelines for modeling complex information-dependent processes in the construction domain.

Visual Basic programming language was used to develop the main prototype that was then integrated with commercial collaboration tools. The proposed system can be used by design firms to store building data, record design rationale, manage the multidisciplinary design changes, and share design information. In the following sections, the components of the proposed system are explained and a detailed case study is presented.

## 5.2 The Proposed Collaborative System

As shown in Fig. 5.1, the proposed collaborative system integrates a client/server design environment with a set of collaboration tools. The client/server environment is based on the information model that was presented in Chapter 4. The information model is composed of three main parts: 1) the building project hierarchy (BPH); 2) the building components library (BCL); and 3) the design-change management (DCM) procedures (Fig. 4.5, Chapter 4). Conceptual details of the information model parts are described in Chapter 4.

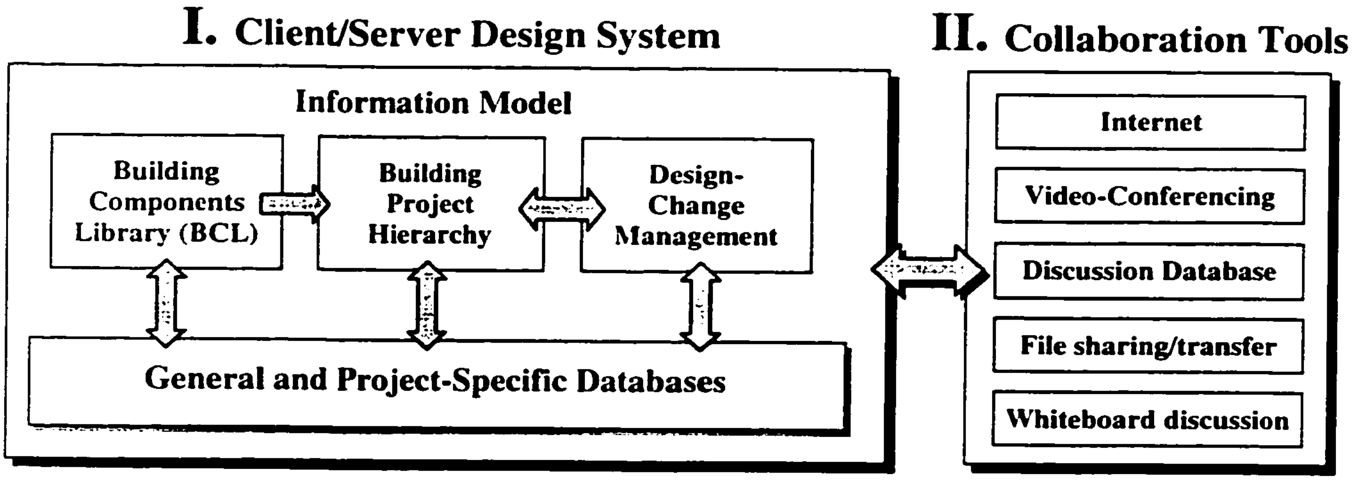


Fig. 5.1. The Proposed Collaboration System.

In addition to the client /server system for building design, a host of collaboration tools are integrated into it to improve design productivity and facilitate Internet-based coordination. The implementation of the client/server design system and the collaboration tools are described in detail in the following sections.

## 5.3 Client/Server Design System

The proposed client/server design system was implemented on Microsoft Visual Basic 6.0 Enterprise Edition (Microsoft Visual Basic 6.0), which allows client/server developments. The choice of this programming language is due to its object-oriented programming features, relative ease-of-use, ability to integrate with Microsoft collaboration tools, and rapid prototyping.

### 5.3.1 System Databases

At the core of the client/server system is a group of databases developed using Microsoft Access (Microsoft Access 97), which are directly readable by Visual Basic code (Appendix A). One project-independent database is used to store default building components in the BCL. In addition, each design project requires five databases (Fig. 5.2): four databases to store the multidisciplinary BPH data for the architectural, structural, mechanical, and electrical designs; and a fifth database to store the short-term and long-term design changes (i.e., proposed changes and applied changes, respectively) in two tables within the database.

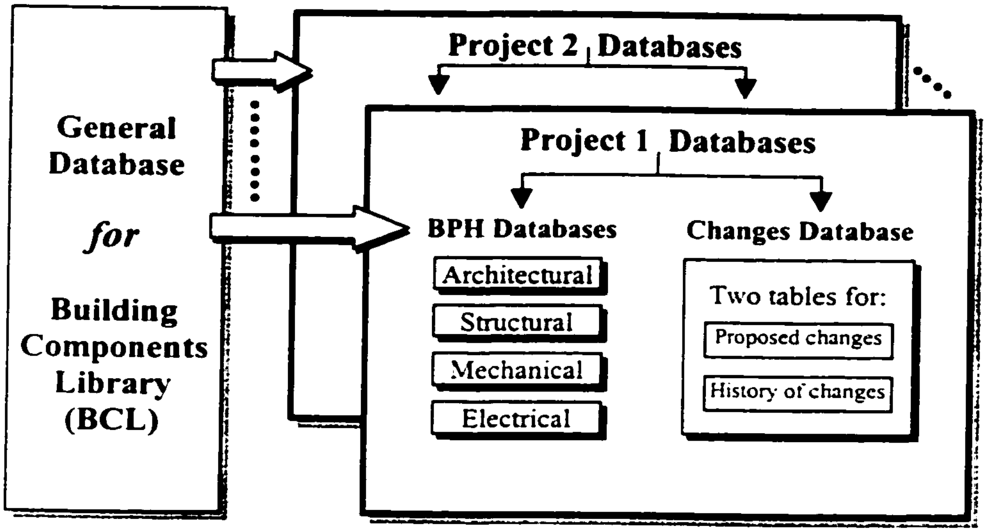
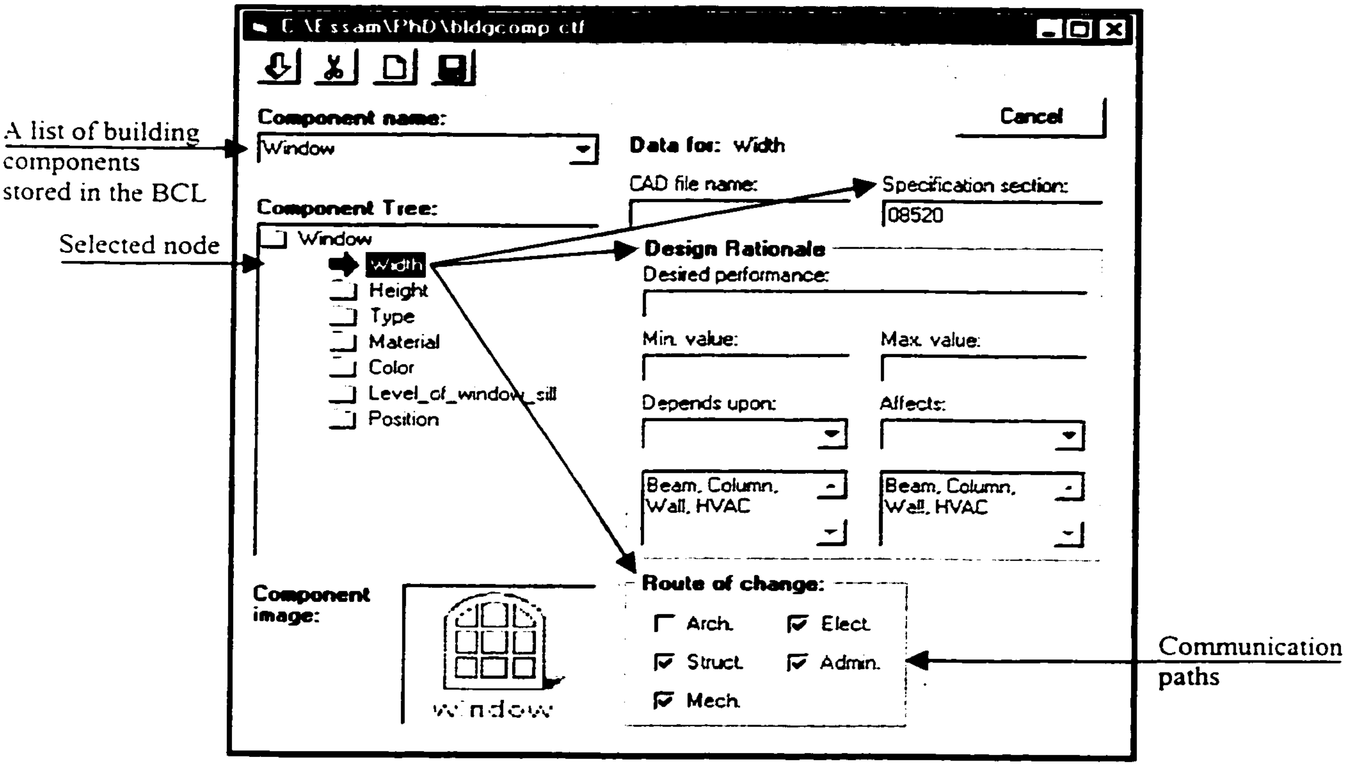


**Fig. 5.2. The Proposed System Databases.**

### 5.3.2 Building Components Library (BCL)

The BCL is a central repository of all building components that are used by all design participants to create a complete BPH for a project. All the information related to the BCL are stored in the "BCL database", which is accessible to all design projects. Default components from various levels (e.g., floor, space, door, window, wall, beam ,column, etc.) are stored in the BCL. Fig. 5.3, for example, shows the interface to the BCL with a default window component. As shown in the figure, the width object of the window has been assigned default specification section, design rationale, and communication paths. Similarly, 27 components from all design disciplines having a total of 205 attributes were stored in the BCL of the proposed system (Table 5.1).



Component name: Window

Data for: Width

CAD file name:

Specification section: 08520

Desired performance:

Min. value:

Max. value:

Depends upon: Beam, Column, Wall, HVAC

Affects: Beam, Column, Wall, HVAC

☐ Arch. ☑ Elect.
☑ Struct. ☑ Admin.
☑ Mech.

**Fig. 5.3. Building Components Library (BCL).**

Only the design administrator has "copy/modify" access to the BCL while all designers have the "copy-only" access to use it to add components from BCL to the BPH. The information in the BCL, therefore, is maintained with a high level of consistency and security. Using the window form of Fig. 5.3, the administrator can add new default components to the BCL and then specify the design discipline that can use that component. Once default values for the specification section, design rational, and route of changes (communication paths) are specified, the default component is added to the BCL and then becomes ready for use by designers.

**Table 5.1: Some of the Components Stored in the BCL.**

| Discipline | Component Name | Suggested Attributes |
|---|---|---|
| Architectural | Project information | Site width, site length, number of buildings, allowable building height, total built-up area, setbacks |
| | Building | Overall height, built-up area, type of construction, external finishing |
| | Floor | Finish thickness, level, area, clear height, false ceiling height, floor-to-ceiling height, floor-to-floor height |
| | Roof floor | Finish thickness, level, area, parapet height, screed slope, waterproofing, insulation, structural branch, mechanical branch, electrical branch |
| | Stair | Material, width, length, riser height, tread width, number of steps, finish material, finish thickness |
| | Space | Width, length, clear height, floor-finish thickness, floor-finish material, floor-finish color, architectural branch, structural branch, mechanical branch, electrical branch |
| | Ceiling | Finishing, false-ceiling type, false-ceiling height |
| | Door | Width, height, type, material, color, position |
| | Window | Width, height, type, material, color, level of window-sill, position |
| | Partition wall | Height, thickness, material, finishing, position |
| | Wall | Height, thickness, internal finish, external finish, insulation, position |
| Structural | Concrete solid slab | Concrete strength, concrete type, steel strength, thickness, reinforcement, code restrictions |
| | Beam | Concrete strength, concrete type, steel strength, allowable depth, depth, width, material, reinforcement, code restrictions, position |
| | Column | Concrete strength, concrete type, steel strength, depth, width, material, reinforcement, code restrictions, position |
| | Concrete wall | Concrete strength, concrete type, steel strength, thickness, height, reinforcement, code restrictions, name of architectural wall, position |
| | Slab-on-grade | Concrete strength, concrete type, steel strength, thickness, reinforcement, vapor barrier |
| | Spread footing | Allowable soil bearing capacity, concrete strength, concrete type, steel strength, bottom level, blinding concrete, column width, column depth, column reinforcement, footing thickness, footing width, footing length, footing reinforcement, position |
| Mechanical | HVAC duct | Allowable depth, depth, width, type, material, insulation, position |
| | Diffuser | Type, opening size, insulation, position |
| | Drainage pipe | Type, material, diameter, number of bends, position |
| | Floor drain | Type, material, size, position |
| Electrical | Conduit | Type, size, position |
| | Panelboard | Type, width, depth, feeder type, feeder size, position |
| | Lighting fixture | Type, illumination, size, color, position |

### 5.3.3 Building Project Hierarchy (BPH)

As opposed to the BCL, which is general, the BPH is project-specific. The BPH allows a unified storage and manipulation of building data that promotes consistency and avoids redundancy. All building components in the BPH are represented as smart objects that contain all their multidisciplinary design information. As such, the BPH is a spatial decomposition of the building in which each space contains information related to its architectural, structural, mechanical, and electrical designs.

The main menu of the proposed design system is shown in Fig. 5.4. The architect can initiate a new project and create its BPH by simply answering four questions related to: 1) new project name; 2) number of buildings in the project; 3) number of floors in each building; and 4) number of spaces in each floor.

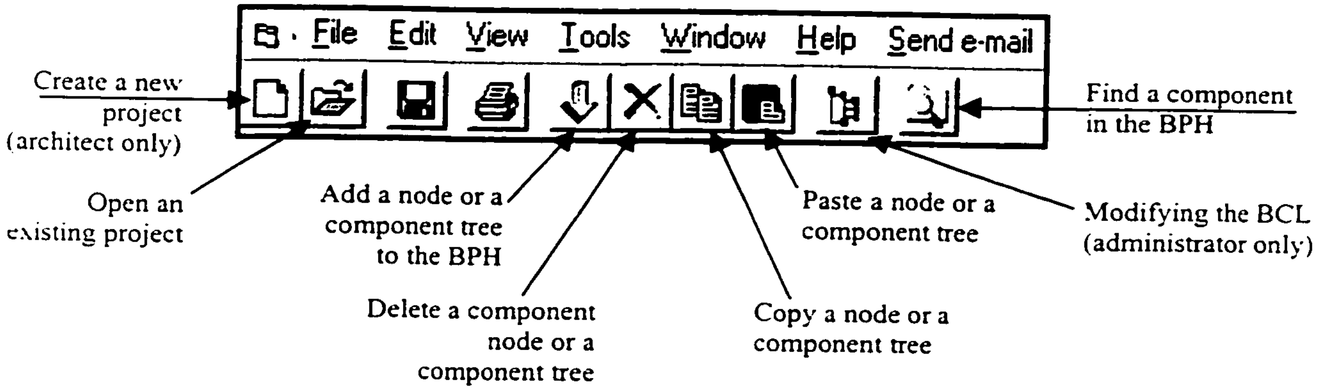
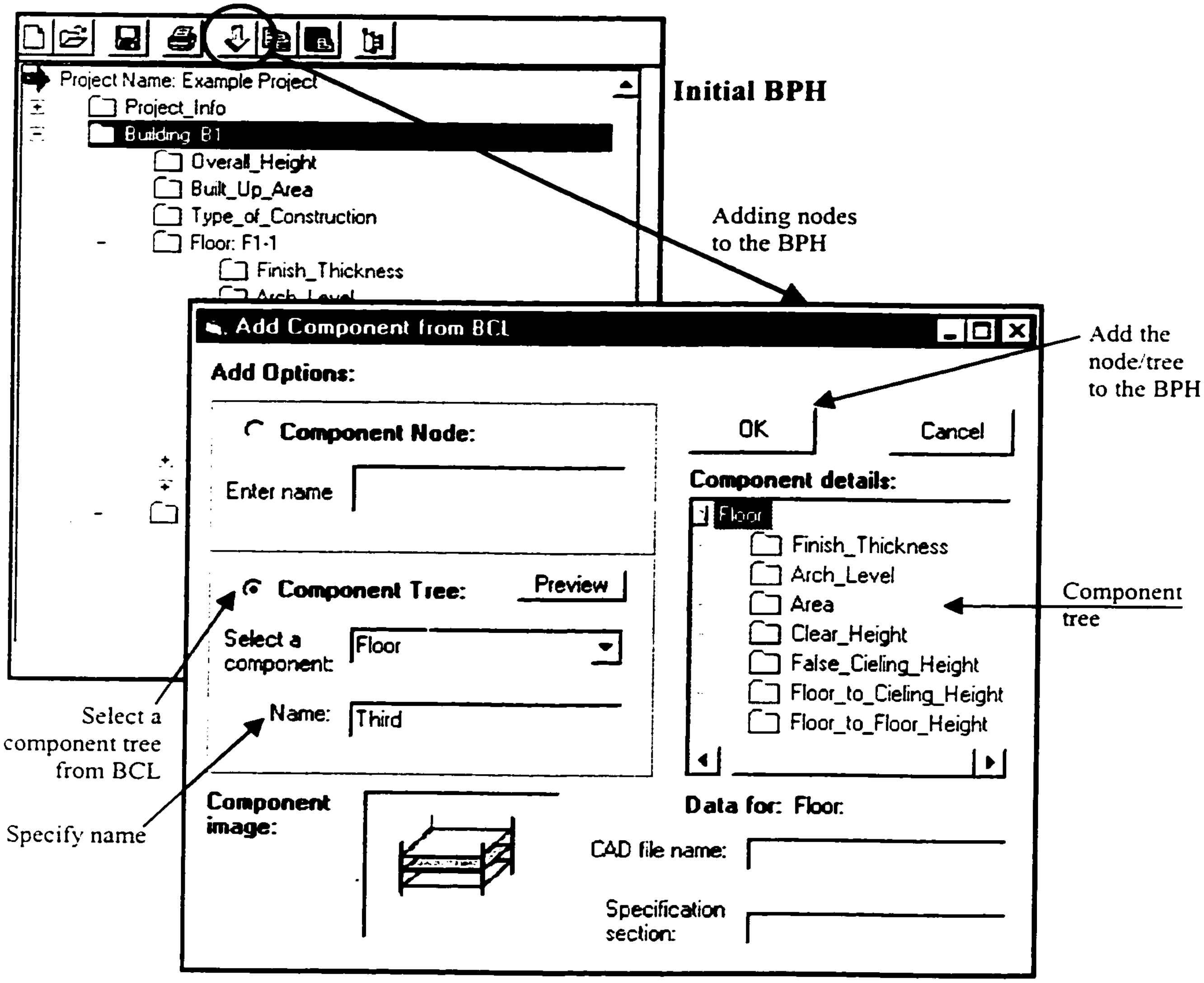


Fig. 5.4. The Main Menu of the Proposed Collaboration System.

Accordingly, a default BPH (Fig. 5.5) with a roof component will be created along with its underlying databases for the architectural, structural, mechanical, and electrical designs. The project shown in Fig. 5.5 consists of one building with 2 floors, 2 spaces in each floor, and a roof. Since the building contains more than one floor, a stair component was automatically added to the BPH. To refine the initial BPH as per the detailed project information, the architect can change the default names of the components (nodes) and also use the BCL to add new components to the BPH, as illustrated in Fig. 5.5. Following this process, the system main screen will be as shown in Fig. 5.6, with the BPH shown in the left side of the screen.

Adding lower level components (e.g., door, window, beam, column, etc.) from the BCL to the BPH is simple as it relates to a single design discipline. Adding a higher level component such as "space", on the other hand, adds various default nodes that relate to the architectural, structural, mechanical, and electrical systems within the space. The "Conference room" space in Fig. 5.6, for example, was inserted initially as a default component from the BCL with its sub-nodes including the systems nodes. With the "structural" node of the "Conference room" space being highlighted, its associated structural tree is read from the "structural" database and is automatically shown at the bottom of the screen (Fig. 5.7). With any node being selected, all of its values appear and allow the designer to



Project Name: Example Project

Add Component from BCL

Add Options:

○ Component Node:

Enter name

● Component Tree:

Select a component: Floor

Name: Third

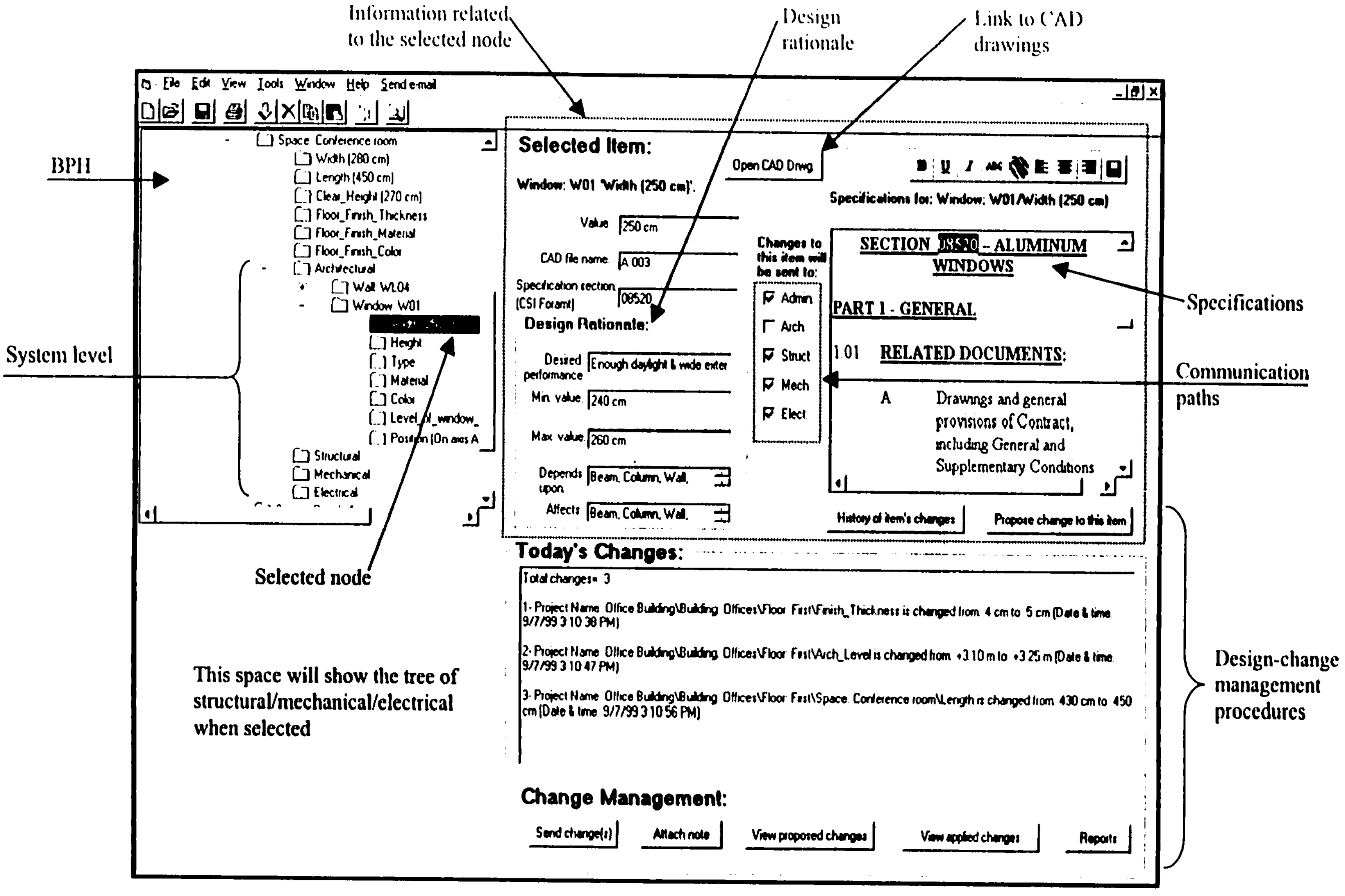
Component details:

Data for: Floor

CAD file name:

Specification section:

Fig. 5.5. Using the BCL to Add Components to the BPH.



Space Conference room
☐ Width (280 cm)
☐ Length (450 cm)
☐ Clear_Height (270 cm)
☐ Floor_Finish_Thickness
☐ Floor_Finish_Material
☐ Floor_Finish_Color
☐ Architectural
☐ Wall WL04
☐ Window W01
☐ Height
☐ Type
☐ Material
☐ Color
☐ Level_of_window_
☐ Position (On axis A
☐ Structural
☐ Mechanical
☐ Electrical

This space will show the tree of structural/mechanical/electrical when selected

**Selected Item:**

Window: W01 'Width (250 cm)'.

Value: 250 cm

CAD file name: A 003

Specification section (CSI Format): 08520

**Design Rationale:**

Desired performance: Enough daylight & wide exter

Min value: 240 cm

Max value: 260 cm

Depends upon: Beam, Column, Wall,

Affects: Beam, Column, Wall,

Changes to this item will be sent to:
☑ Admin
☐ Arch
☑ Struct
☑ Mech
☑ Elect

Specifications for: Window: W01/Width (250 cm)

SECTION 08520 - ALUMINUM WINDOWS

PART 1 - GENERAL

1.01 RELATED DOCUMENTS:

A Drawings and general provisions of Contract, including General and Supplementary Conditions

**Today's Changes:**

Total changes= 3

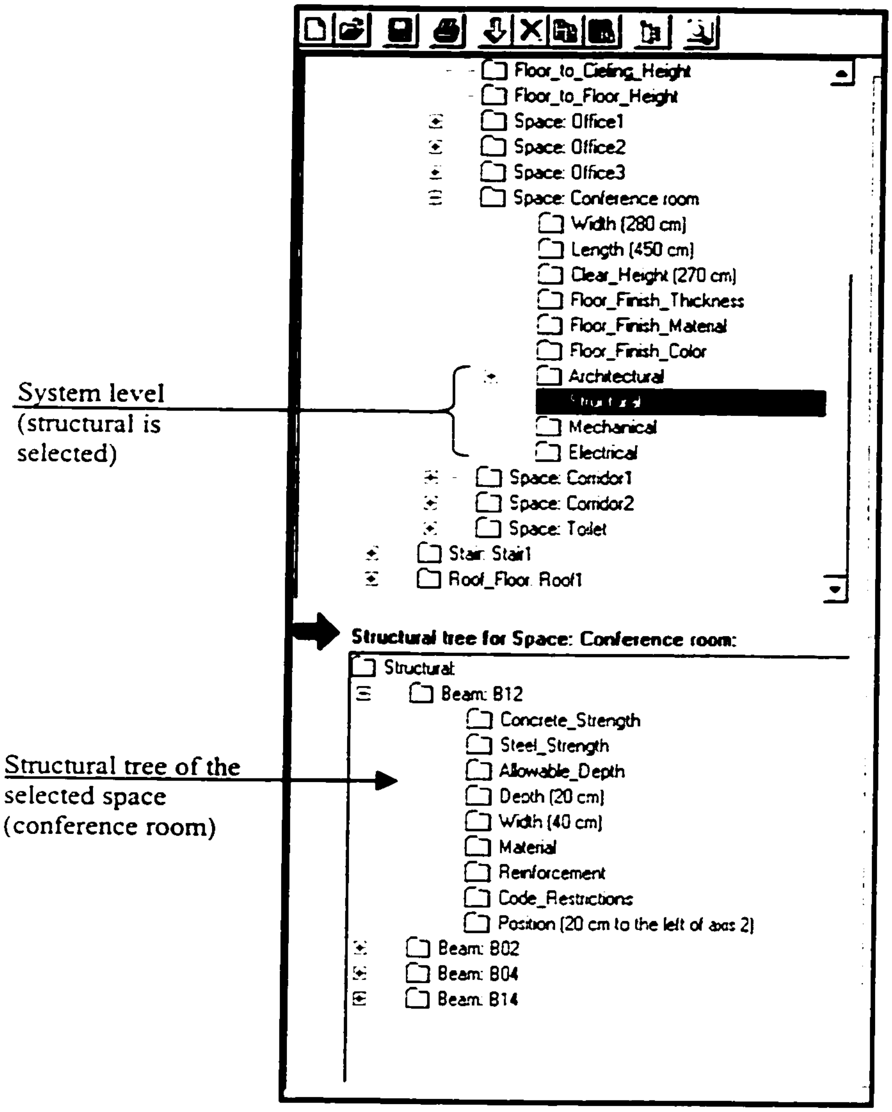
1- Project Name Office Building\Building Offices\Floor First\Finish_Thickness is changed from 4 cm to 5 cm (Date & time 9/7/99 3 10 38 PM)

2- Project Name Office Building\Building Offices\Floor First\Arch_Level is changed from +3 10 m to +3 25 m (Date & time 9/7/99 3 10 47 PM)

3- Project Name Office Building\Building Offices\Floor First\Space Conference room\Length is changed from 430 cm to 450 cm (Date & time 9/7/99 3 10 56 PM)

**Change Management:**

Fig. 5.6. Main Screen of the Proposed Collaboration System.



- Floor_to_Ceiling_Height
- Floor_to_Floor_Height
- Space: Office1
- Space: Office2
- Space: Office3
- Space: Conference room
  - Width (280 cm)
  - Length (450 cm)
  - Clear_Height (270 cm)
  - Floor_Finish_Thickness
  - Floor_Finish_Material
  - Floor_Finish_Color
  - Architectural
  - Structural
  - Mechanical
  - Electrical
- Space: Corridor1
- Space: Corridor2
- Space: Toilet
- Stair: Stair1
- Roof_Floor: Roof1

**Structural tree for Space: Conference room:**

- Structural
  - Beam: B12
    - Concrete_Strength
    - Steel_Strength
    - Allowable_Depth
    - Depth (20 cm)
    - Width (40 cm)
    - Material
    - Reinforcement
    - Code_Restrictions
    - Position (20 cm to the left of axis 2)
  - Beam: B02
  - Beam: B04
  - Beam: B14

System level (structural is selected)

Structural tree of the selected space (conference room)

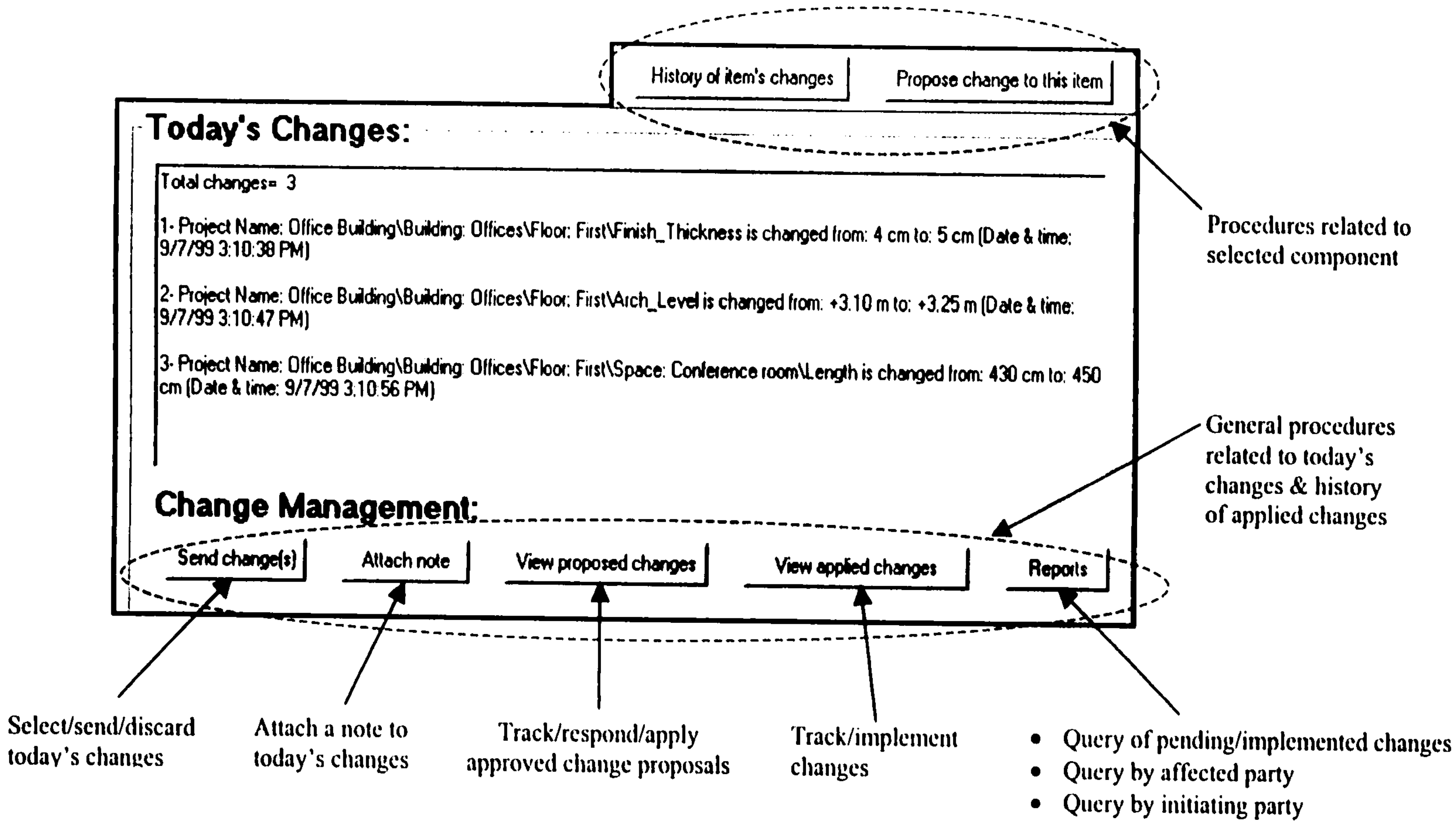
Fig. 5.7. Multidisciplinary Building Project Hierarchy (BPH).

edit/modify its information related to CAD/specification documents and design rationale, as shown in the right side of Fig. 5.6. Designers, however, will not be able to modify part of the design rationale and communication paths directly from the BPH. If such a modification is necessary, the design administrator should be consulted for this purpose. This is important in order to maintain the required consistency and ensure the system's security.

### 5.3.4 Managing Design Changes

One of the main features of BPH components is their being active objects capable of automatically communicating changes made to their own values. To facilitate design change management, component-related procedures are included for monitoring new and old values of any object attribute, allowing the designer to propose new values and obtain approval from other disciplines before doing a change, and tracking/sending/finding changes made to the component. In addition to these component-related procedures, other general procedures were included as part of the change management module. The general procedures (Fig. 5.8) provide effective tracking of all changes made, allow designers to respond to proposed changes, implement approved change-proposals, and obtain various reports on the changes made. These procedures improve coordination and keep project information up to date.

When a designer uses the system, all the changes he makes are stored in a temporary database "today's-changes". This information is then transferred to the project's "changes" database at the designer's request (using the "Send change(s)" button shown in Fig. 5.8). The "changes" database includes two tables; one for the "proposed changes" and the other for the "applied changes". The reporting system queries these databases to provide the user with useful



Today's Changes:

Total changes= 3

1- Project Name: Office Building\Building: Offices\Floor: First\Finish_Thickness is changed from: 4 cm to: 5 cm (Date & time: 9/7/99 3:10:38 PM)

2- Project Name: Office Building\Building: Offices\Floor: First\Arch_Level is changed from: +3.10 m to: +3.25 m (Date & time: 9/7/99 3:10:47 PM)

3- Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is changed from: 430 cm to: 450 cm (Date & time: 9/7/99 3:10:56 PM)

Change Management:

Fig. 5.8. Design-Change Management Procedures.

information regarding pending changes and the history of changes made during the design evolution. SQL statements were used to automatically query these databases and obtain the status of changes made by (or affect) any design discipline.

## 5.4 Collaboration Tools

The proposed collaborative system has been linked with Microsoft Windows NetMeeting, Version 3.01 (Microsoft Windows NetMeeting), an Internet-based collaboration tool. This tool provides many features such as video and audio conferencing, real-time whiteboard collaboration, real-time chatting, file sharing, and file transfer during a NetMeeting conference (Fig. 5.9).

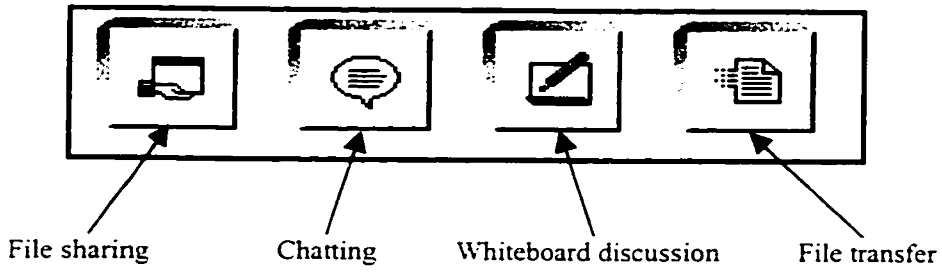


**Fig. 5.9. Features of the Collaboration Tool.**

Since the proposed system is developed based on Visual Basic programming language, one of Microsoft software family, it can be integrated with the new Microsoft products. The present system implementation has been carried out on machines with Windows 95 and Microsoft Office 1997. For testing purposes, the machines were linked to the University of Waterloo Local Area Network (LAN). Also, various other commercial collaboration tools can be integrated with the system, as discussed later under Chapter 7.

## 5.5 Implementation Issues and Solutions

Implementing the collaboration system was neither simple nor a straightforward task. Several implementation issues had to be addressed, related to:

1. Establishing access control/access rights
2. Ensuring the independence of each design discipline
3. Saving and loading BPH trees
4. Managing BCL components
5. Specifying components at space boundaries
6. Controlling the communication of changes
7. Enforcing change proposals
8. Applying, sending, and discarding changes
9. Facilitating designers response to changes
10. Developing automated warning

Addressing these issues mandated iterative cycles of refinement to the model and substantial programming effort. A discussion on how these issues were resolved provides guidelines to other researchers in the academia when developing similar complex systems. The solutions made with respect to these implementation issues are described in the following.

**5.5.1 Establishing Access Control/Access Rights:** A password-based access control was used in the proposed system to identify the user's discipline type and accordingly specify his access rights to the BPH and the BCL. Designers from all disciplines can only modify their part of the BPH and view the work of all others. Only the administrator has the copy/modify access to the BCL while other designers can only use the BCL to add components to the BPH (Fig. 5.10). Also, according to the user's discipline type, all screens and change management options directly provide designers with all data relevant to their own discipline to remind them of important responses to make and/or changes to implement. The reporting features also provide designers with a list of all changes made by other disciplines that affect their design and the changes they made and affect other disciplines.

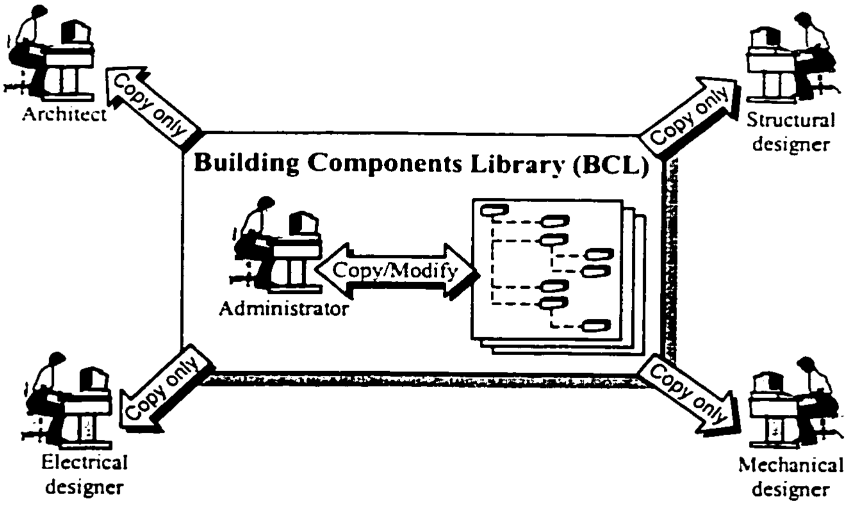


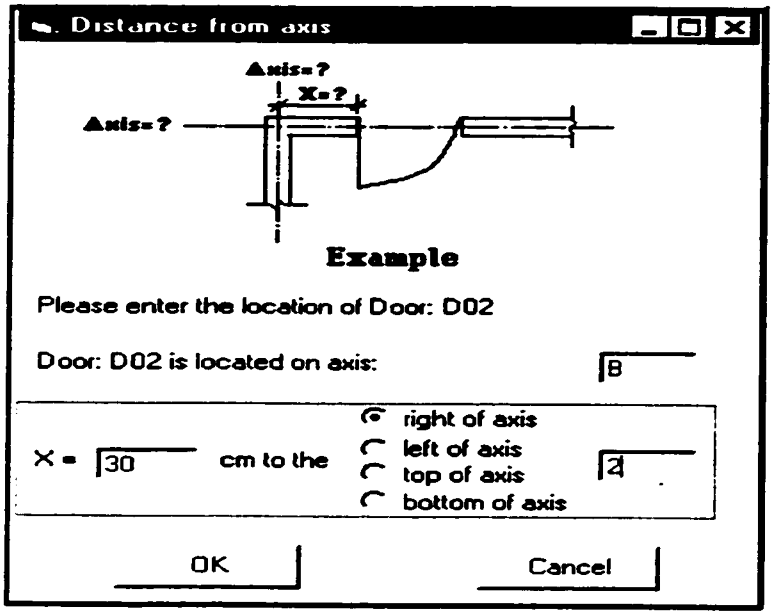
Fig. 5.10. Access Control to BCL.

**5.5.2 Ensuring the Independence of Each Design Discipline:** In normal cases, when a certain component tree is copied from one branch in the BPH and pasted to another, the data included in that tree will be copied with it. This creates a problem when the architect, for example, tries to copy the tree of an existing space and paste it to generate a new space. In this case, the structural, mechanical, and electrical branches underneath the original space will be copied to the new location, thus forcing unapproved additions to the work of these disciplines, not only the architectural. To solve this problem, the copy and paste procedures were modified so that the structural, mechanical, and electrical nodes are copied, without their underlying trees. The structural, mechanical, and electrical designers, however, can copy and paste their own designs to other locations. As such, no discipline can introduce/change the design work related to other disciplines.

**5.5.3 Saving and Loading BPH Trees:** Having a single project BPH that is accessed and modified by all disciplines causes the work of each discipline to be scattered in different places in the BPH. This might create a problem when saving and loading each discipline's work and the whole BPH. Proper database design, therefore, was a key to the success of the proposed BPH representation. The BPH data, therefore, are saved in four separate databases for the architectural, structural, mechanical, and electrical design data, with the architectural database having links to the other databases to facilitate the generation of the whole BPH tree during project loading. The structure of the structural, mechanical, and electrical databases is similar and incorporates a number of tables, each saving the subtrees associated with a different space component in the BPH. In this manner, a unified BPH representation of all the multidisciplinary design information is achieved.

**5.5.4 Managing BCL Components:** To manage the different components in the BCL, a reference to its discipline type is used. An architectural component such as a door or a window, for example, can have an "A" reference so that it can be accessed only by architects. As such, each design discipline can only use the BCL to add components related to its part of the BPH.

**5.5.5 Specifying Components at Space Boundaries:** Many components such as doors, windows, walls, columns, footings, etc. may exist at the boundaries between two or more spaces in the BPH. Adding these components to all spaces, therefore, will create redundant information and makes the administration of changes more difficult since any changes have to be made to all instances of that component. To address this issue, the location of the component on the boundary line is specified by the user and a procedure for checking adjacent spaces is included. Input screens were designed for specifying the location of door, window, wall, beam, column, and footing components (e.g., Fig. 5.11). Door (D02) shown in the figure, for example, is located on axis "B" and at 30 cm to the right of axis "2". This location information need to be stored under any one space in the BPH that share the boundary (Axis B). If a designer attempts to add the same component to an adjacent space, its location will be checked in all adjacent spaces and, accordingly, it will not be added. Also, to facilitate user access to any component and allow designers to easily find components in the BPH, a search routine was included (Fig. 5.12).



Please enter the location of Door: D02

Door: D02 is located on axis: B

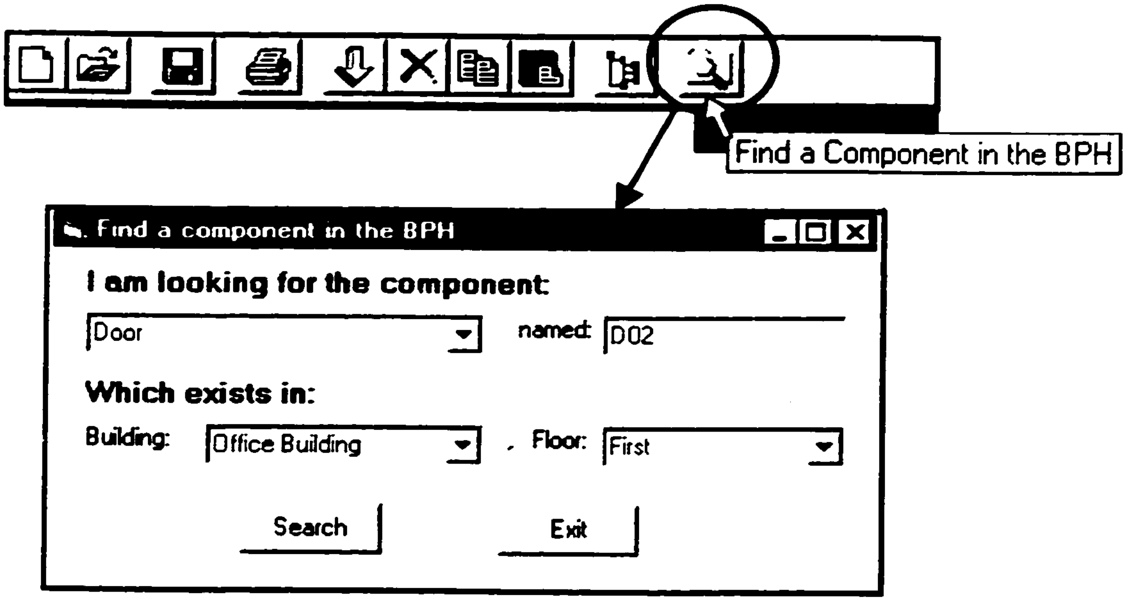
X = 30 cm to the

● right of axis
○ left of axis
○ top of axis
○ bottom of axis

2

Fig. 5.11. Specifying the Location of a "Door" Component.

**5.5.6 Controlling the Communication of Changes:** At the early stage of generating a new project, it may not be practical to send every change made to the BPH. The architect, for example, may frequently change the dimensions of spaces before deciding on their final values. Once these are finalized, he may want to start the communication process with other disciplines. To allow this flexibility, the proposed system allows the administrator to turn the process of sending changes on and off (Fig. 5.13). The default option in the proposed system is to "lock send changes".



Find a component in the BPH

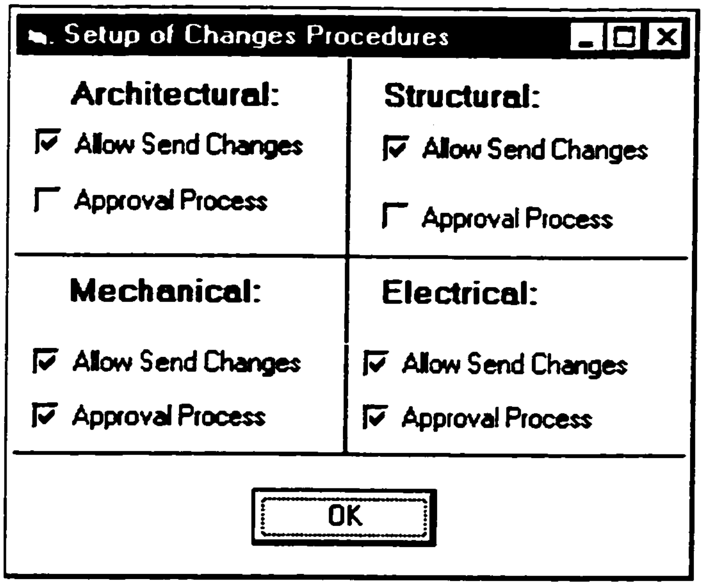
**I am looking for the component:**

Door named: D02

**Which exists in:**

Building: Office Building , Floor: First

Fig. 5.12. Searching for a Component in the BPH.



Setup of Changes Procedures

**Architectural:**
☑ Allow Send Changes
☐ Approval Process

**Structural:**
☑ Allow Send Changes
☐ Approval Process

**Mechanical:**
☑ Allow Send Changes
☑ Approval Process

**Electrical:**
☑ Allow Send Changes
☑ Approval Process

Fig. 5.13. Options for Managing Design Changes.

**5.5.7 Enforcing Change Proposals:** Using the proposed system, designers from each discipline can change their design at anytime. In some cases, however, particularly at later stages of the design where frequent changes may be costly and disruptive, it may be necessary to apply the changes made only after consultation and approval from all other disciplines. To allow this flexibility, the proposed system allows the administrator to enforcing an approval process for design changes or allow direct changes by designers without going through an approval process (Fig. 5.13). The default option in the proposed system is to use the "non-approval process". With the approval process in place, special procedures were written to track the parties who responded to a certain change-proposal and to notify designers when all parties approve a change-proposal so that it can be implemented.

**5.5.8 Applying, Sending, and Discarding Changes:** All changes made by a designer during one session, including the ones that received approvals, are saved temporarily on the "today's changes" database. To allow flexibility in discarding or saving any changes, the "today's changes" database includes information related to the old and the new values for the changed nodes. Discarding some of the changes required a search mechanism in order to replace the new values of unselected changes in the BPH with their old values.

**5.5.9 Facilitating Designers Response to Changes:** When a designer receives either a proposed change or an applied change, it is sometimes useful if the designer is reminded of the components that are influenced by the change. In the proposed system, since this information can be stored in the design rationale, it is sent with the old and new values as an important information related to the change and, accordingly, stored in the changes database. As a possible extension to the proposed system, information related to the affected components can be used to trace the ripple effect of the changes made to a project by drawing a network of the consecutive changes made (e.g., Fig. 5.14). This can help in determining the impact of changes on other components in the project.

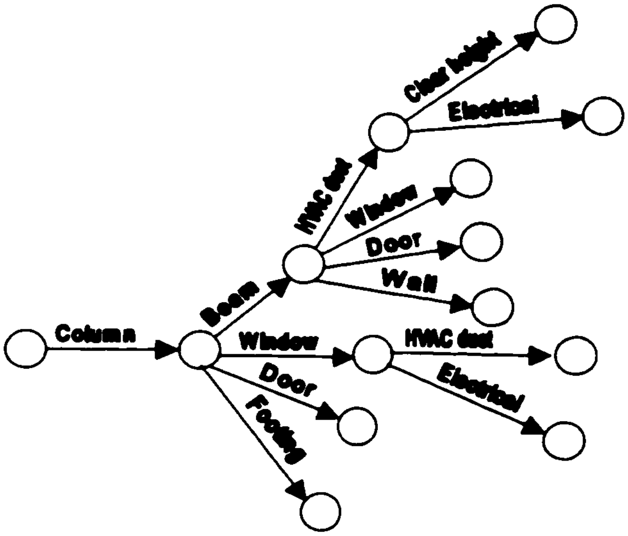


Fig. 5.14. Impact of Design Changes.

**5.5.10 Developing Automated Warning:** With many changes being introduced during design evolution, it is possible that some designers may not implement some changes on a timely fashion or omit to implement a change. To avoid this, a powerful warning system is developed by writing various procedures to track all changes made to a project and continuously remind designers to respond to pending change-proposals and applied-changes (Fig. 5.15). As shown in the figure, the process starts with a designer proposing a change to a certain component in the BPH. This change proposal is automatically sent to affected parties to respond to it. When all affected parties provide their approval, this change proposal can be applied by the party initiated the change. SQL statements were used to automatically query the changes database and obtain the status of all change-proposals and applied-changes.

If a response to a proposed change is not provided, different messages (depending on the amount of delay) will appear to remind designers to respond, as shown in Table 5.2. Similarly, applied changes are automatically and instantly sent to all affected parties who, in tern, should provide a date to implement the effect of this change on their designs. If a designer did not provide a date to implement (respond to) a change or did not implement a change on time, he will automatically receive different messages as those shown in Table 5.3 to remind him accordingly. It is also necessary to keep track of all late responses and remind designers if a response is still not provided. Therefore, if a designer did not respond for a proposed or an applied change for more than a week, the system will ask him to meet the administrator and provide an explanation for the delay in the response (Tables 5.2 and 5.3).

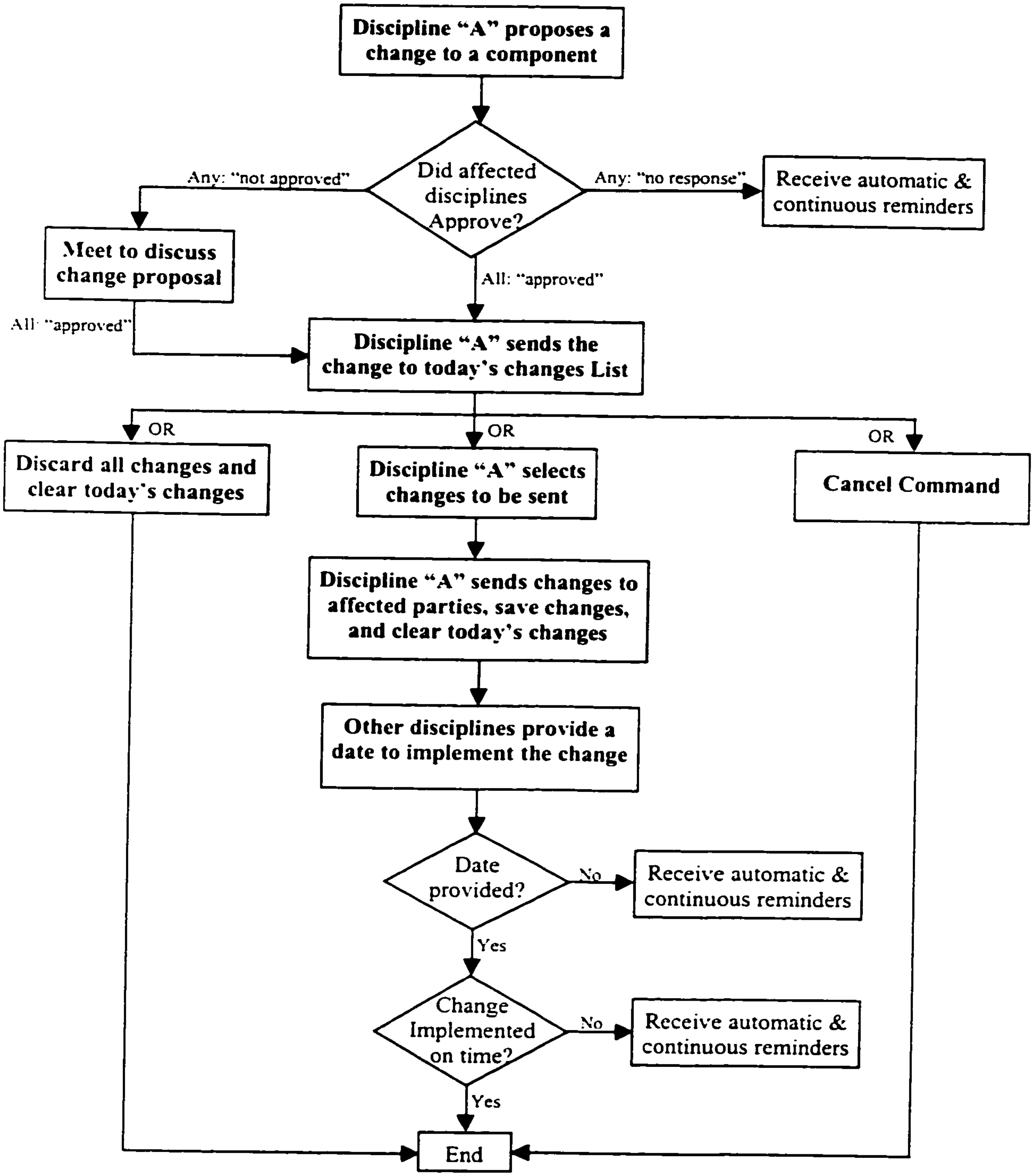


Fig. 5.15. Design-Change Management Mechanism.

**Table 5.2: Massages Asking Response to Proposed Changes.**

| Time | Received Message |
|---|---|
| Time of change proposal | Please respond to this proposed change as soon as possible |
| Within 7 days after change proposal is made | You did not respond to this proposed change for (n)[*] days |
| More than 7 days after change proposal is made | You did not respond to this proposed change for (n)[*] days. Please contact the administrator or provide an explanation |
| Date of receiving response | Thanks for responding to this proposed change |

[*] n = the difference between today's date and the date of receiving the change proposal.

**Table 5.3: Messages Asking Response to Applied Changes.**

| Time | Case | Received Message |
|---|---|---|
| Date of receiving change | No implementation date provided | Please provide a date to implement this change as soon as possible |
| Within 7 days of receiving a change | | You did not provide a date to implement this change for (n1)[*] days |
| More than 7 days after receiving a change | | You did not provide a date to implement this change for (n1)[*] days. Please contact the administrator or provide an explanation |
| Before the due date | Implementation date specified | (no message provided) |
| On the due date | | Please note that you are supposed to finish the implementation of this change today |
| Within 7 days after due date | | You are (n2)[**] days late! The implementation of this change is supposed to finish on (the expected date to finish implementation) |
| More than 7 days after due date | | This change is scheduled to be implemented before (n2)[**] days. Please contact the administrator or provide an explanation |
| Change implemented | | Thanks for implementing this change |

[*] n1 = the difference between today's date and the date of receiving the change.

[**] n2 = the difference between today's date and the expected date to finish implementation.

## 5.6 Example

In order to demonstrate the proposed collaborative system, the two-floor concrete building example that was presented in section 4.3 (Chapter 4) is implemented on the proposed system. Some architectural and structural details of this example are shown in Chapter 4 (Fig. 4.8 and Fig.4.9). To simulate the work environment of remote designers, the collaboration system was installed on two machines (one as a client and the other as a server) linked to the University of Waterloo Local Area Network (Fig. 5.16). As shown in the figure, two designers are using the proposed system with an undergoing real-time videoconference during the implementation of this example. The architect is assumed to be at the server location and he was also used as the design administrator, while the structural designer is at the client location.

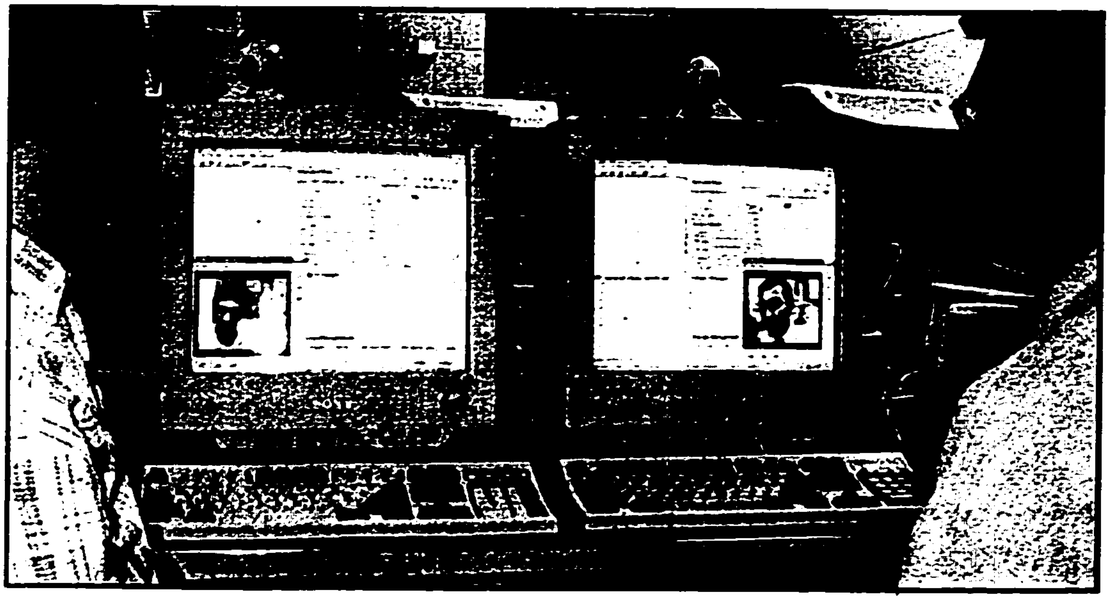
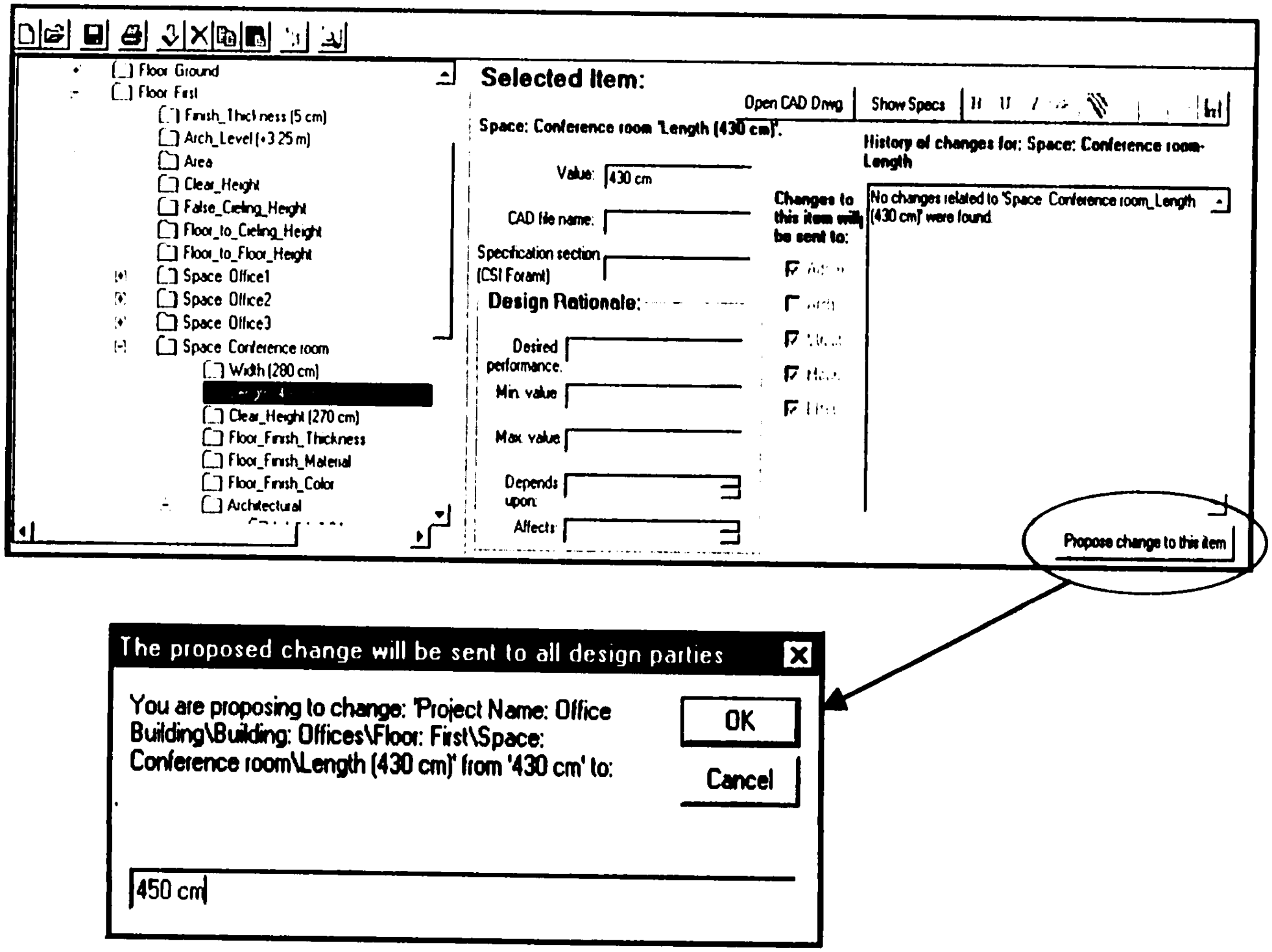


**Fig. 5.16. Simulating Multidisciplinary Design Environment.**

On the server machine, the BPH of this example (Fig. 5.17) was created easily using the default components in the BCL. The structural components were also input on the client machine. A simple change was introduced to the design in which the architect decided to slightly change some dimensions in the first floor and enlarge the conference room by only 20 cm (from 430 to 450 cm). As shown in Fig. 5.17, the architect sent a proposal to change the "Length" of the "Conference room" from 430 cm to 450 cm.

The proposal made by the architect was immediately stored in the "proposed changes" database along with all parties affected by this change (including structural). According to the default communication paths for the conference room length, affected parties are the structural, mechanical, and electrical disciplines. Accordingly, these affected parties instantly received the proposed change. As shown in Fig. 5.18, the structural engineer, for example, received the proposed change and should now respond to it. Following the approval process, structural, mechanical, and electrical disciplines approved the change proposal and, accordingly, the architect was instantly notified of their approval dates, thus, allowing him to apply this change (Fig. 5.19). By applying the change, the BPH node representing the "conference room length" will automatically change its value from 430 cm to 450 cm. Since all nodes in the BPH are active objects that



Space: Conference room 'Length (430 cm)'.

Value: 430 cm

CAD file name:

Specification section (CSI Forant)

Desired performance:

Min value

Max value

Depends upon:

Affects:

History of changes for: Space: Conference room-Length

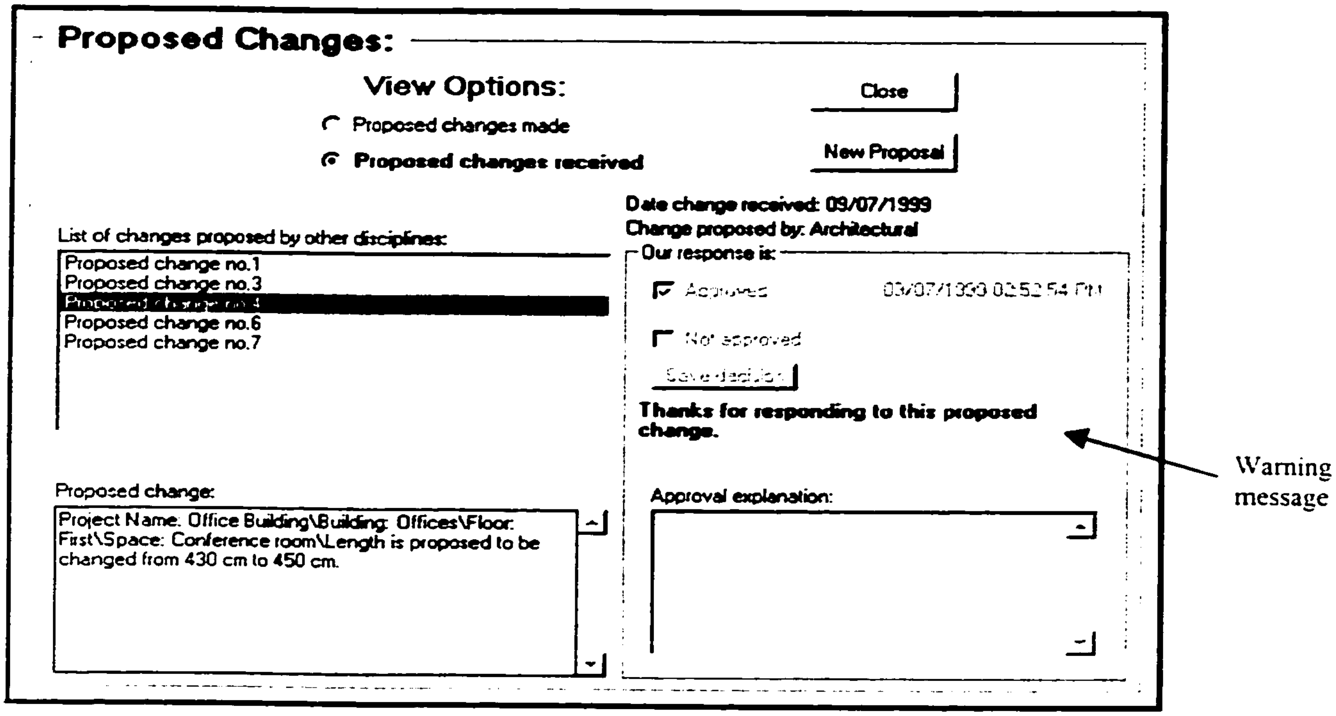
No changes related to 'Space Conference room_Length (430 cm)' were found

The proposed change will be sent to all design parties

You are proposing to change: 'Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length (430 cm)' from '430 cm' to:

450 cm

Fig. 5.17. A Change Proposed by the Architect for the Case Study.



**Proposed Changes:**

**View Options:**

○ Proposed changes made

● **Proposed changes received**

List of changes proposed by other disciplines:

Proposed change no.1
Proposed change no.3
Proposed change no.4
Proposed change no.6
Proposed change no.7

**Date change received: 09/07/1999**
**Change proposed by: Architectural**

Our response is:

☑ Approved 09/07/1999 02:52:54 PM

☐ Not approved

**Thanks for responding to this proposed change.**

Proposed change:

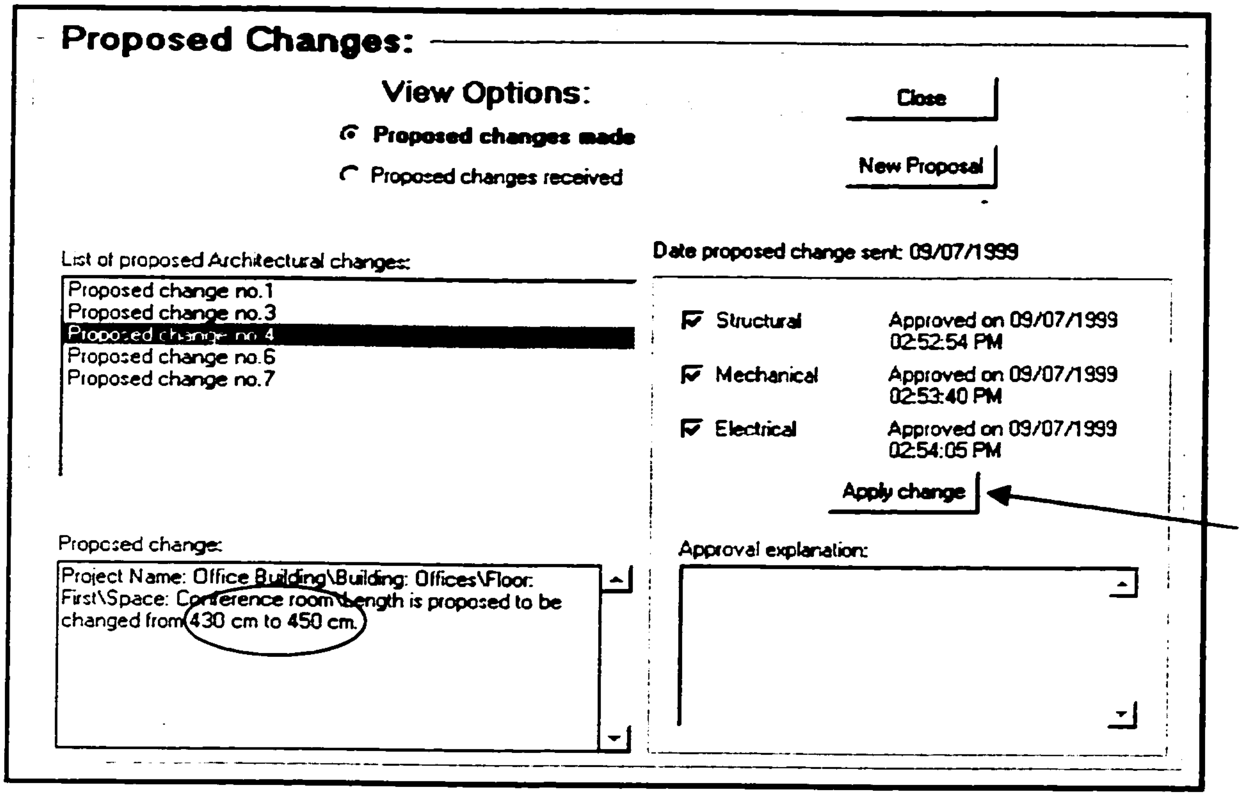
Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is proposed to be changed from 430 cm to 450 cm.

Approval explanation:

Warning message

Fig. 5.18. Changes Proposed by all Other Disciplines and Received by Structural.

are sensitive to changes made to their values, the change will be automatically added to "today's changes" database and stored in it temporarily. After the architect applies this change (in addition to other changes), he can view a list of all these changes and select those that he wants to store permanently in the "changes database" and send to all affected parties (Fig. 5.20). In the BPH, the values of unselected changes, will be replaced with their old values stored in the



**Proposed Changes:**

**View Options:**

● **Proposed changes made**
○ Proposed changes received

List of proposed Architectural changes:

- Proposed change no.1
- Proposed change no.3
- Proposed change no.4
- Proposed change no.6
- Proposed change no.7

Proposed change:

Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is proposed to be changed from 430 cm to 450 cm.

Date proposed change sent: 09/07/1999

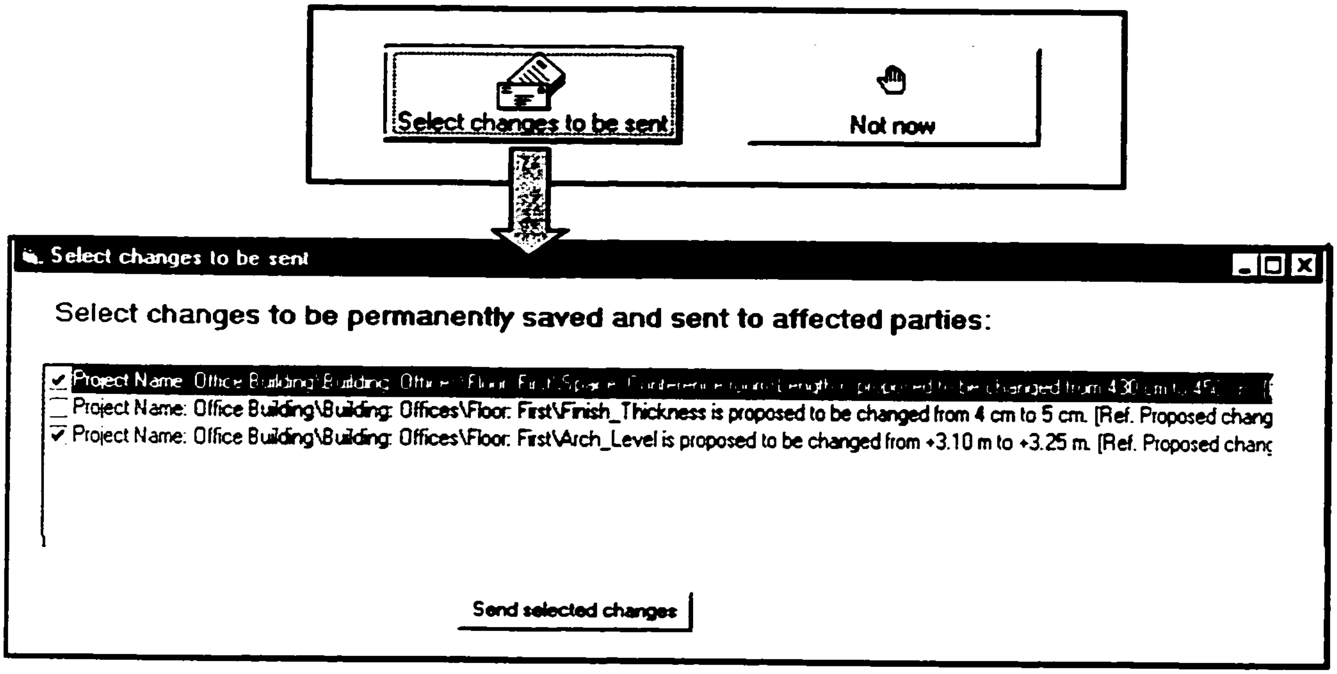
| | |
|---|---|
| ☑ Structural | Approved on 09/07/1999 02:52:54 PM |
| ☑ Mechanical | Approved on 09/07/1999 02:53:40 PM |
| ☑ Electrical | Approved on 09/07/1999 02:54:05 PM |

Approval explanation:

Becomes active when all parties approve the change proposal

Fig. 5.19. Approvals of Other Disciplines to Proposed Changes.

"today's changes" database. Accordingly, the architectural applied change (the conference room length) was sent to affected parties including the structural designer and the system tracks the structural implementation (response) to the applied change (mechanical and electrical are ignored in this example) and uses its warning system (Fig. 5.21) to remind the structural designer of a pending change. As shown in the figure, the structural engineer, for example, received the change applied by the architect (for the conference room length) along with a



Select changes to be permanently saved and sent to affected parties:

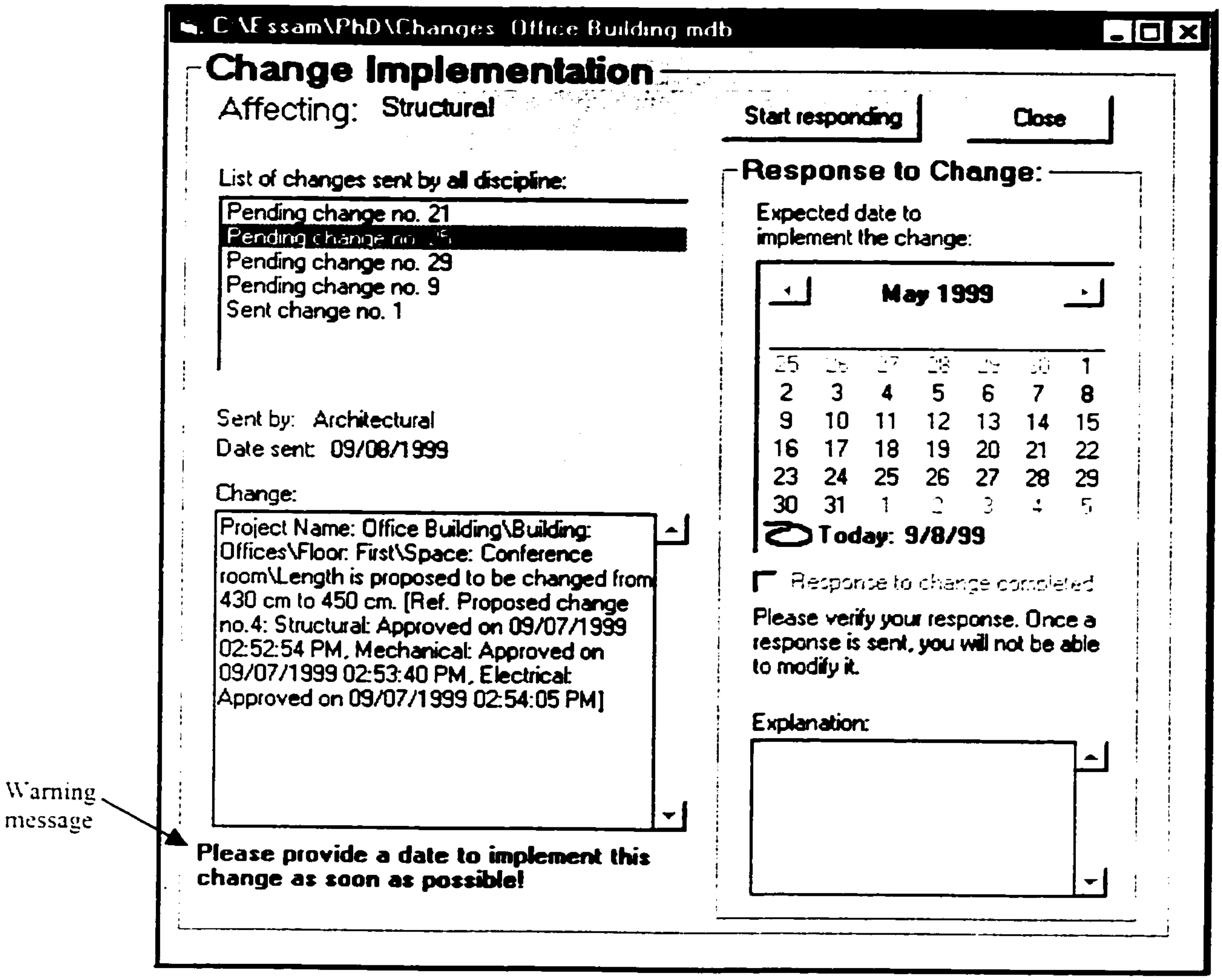
☑ Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is proposed to be changed from 430 cm to 45 [illegible]

☐ Project Name: Office Building\Building: Offices\Floor: First\Finish_Thickness is proposed to be changed from 4 cm to 5 cm. [Ref. Proposed chang

☑ Project Name: Office Building\Building: Offices\Floor: First\Arch_Level is proposed to be changed from +3.10 m to +3.25 m. [Ref. Proposed chanc

Fig. 5.20. Selected Changes to be Stored Permanently and Sent to Affected Parties.

reference to the original change proposal and the dates of the approvals of all affected parties. Accordingly, all affected parties (including the structural engineer) should provide a date on which they expect the effect of this change on their designs will be implemented. Designers from affected disciplines will receive warning messages until a respond is provided for this change. When the structural engineer implements this change, the change will be marked as a "Sent change" in the "changes database", as shown in Fig. 5.21.



Affecting: Structural

List of changes sent by all discipline:

- Pending change no. 21
- Pending change no. 25
- Pending change no. 29
- Pending change no. 9
- Sent change no. 1

Sent by: Architectural

Date sent: 09/08/1999

Change:

Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is proposed to be changed from 430 cm to 450 cm. [Ref. Proposed change no.4: Structural: Approved on 09/07/1999 02:52:54 PM, Mechanical: Approved on 09/07/1999 02:53:40 PM, Electrical: Approved on 09/07/1999 02:54:05 PM]

**Please provide a date to implement this change as soon as possible!**

Expected date to implement the change:

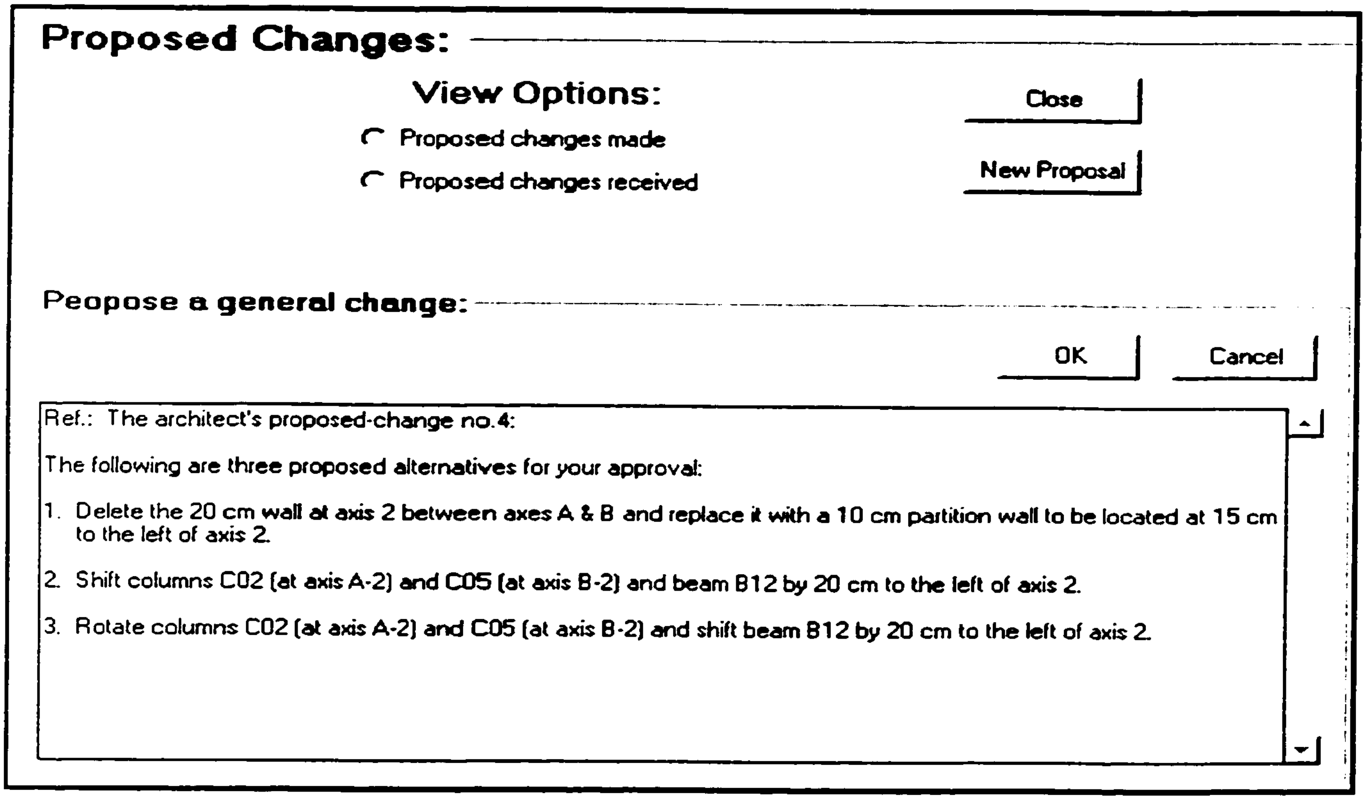
Today: 9/8/99

Please verify your response. Once a response is sent, you will not be able to modify it.

Explanation:

**Fig. 5.21. List of Changes Sent by All Disciplines.**

Before proceeding further, the structural engineer wanted to propose the three alternative solutions shown in Fig. 4.10 (section 4.3, Chapter 4). The first solution is to remove wall (WL04) at axis 2 and replace it with a partition wall located at 15 cm from axis 2. The second solution is to shift wall (WL04) along with columns C02 and C05 and beam B12 that supports the wall by 20 cm. The third solution is to shift wall (WL04) and rotate columns C02 and C05 and shift beam B12 by 20 cm. Using the proposed system, the structural engineer on the client machine sent a general change-proposal that included his three alternative solutions to the applied architectural change (Fig. 5.22). The architect was then assumed to prefer the third solution of rotating columns C02 and C05 and shifting beam B12 by 20 cm. Accordingly, a structural redesign of some columns and beams was necessary, in addition to architectural redesign of the windows to maintain desired daylight criteria. As such, changes trigger other changes and the benefit of the proposed system in monitoring the design evolution process and its changes becomes apparent.



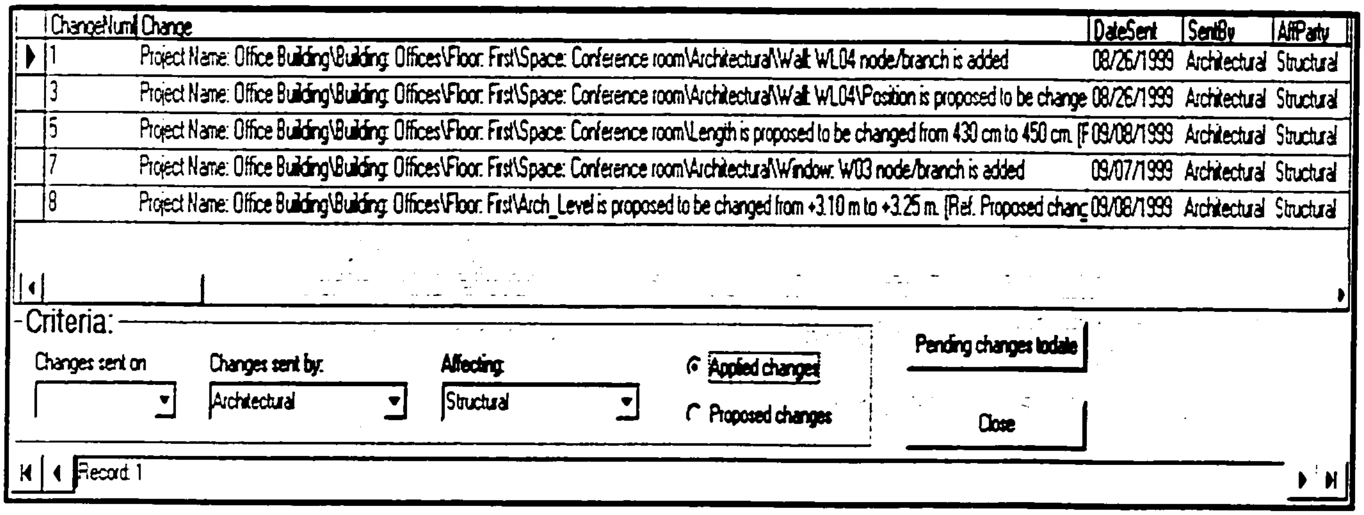
Ref.: The architect's proposed-change no.4:

The following are three proposed alternatives for your approval:

1. Delete the 20 cm wall at axis 2 between axes A & B and replace it with a 10 cm partition wall to be located at 15 cm to the left of axis 2.
2. Shift columns C02 (at axis A-2) and C05 (at axis B-2) and beam B12 by 20 cm to the left of axis 2.
3. Rotate columns C02 (at axis A-2) and C05 (at axis B-2) and shift beam B12 by 20 cm to the left of axis 2.

Fig. 5.22. An Example of a General Change-Proposal.

To facilitate the work of the design administrator, the proposed system also provides various reports that allow all designers to view some or all of the changes related to their design. Two reporting options are provided; to view the "applied changes" and the "proposed changes" (Fig. 5.23). If a designer chooses the "applied changes" option, he can view the changes sent on a certain date, the changes sent by a particular party, and the changes affecting a particular party. Choosing the "proposed changes" option, on the other hand, will allow the designer to view the proposed changes sent on a certain date, the proposed changes sent by a particular party, and the response made by a particular party. The design administrator can use these reports to follow up on pending changes on a daily basis and to track the history of all changes made to the project.



| ChangeNum | Change | DateSent | SentBy | AffParty |
|---|---|---|---|---|
| 1 | Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Architectural\Wall: WL04 node/branch is added | 08/26/1999 | Architectural | Structural |
| 3 | Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Architectural\Wall: WL04\Position is proposed to be change | 08/26/1999 | Architectural | Structural |
| 5 | Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Length is proposed to be changed from 430 cm to 450 cm. (F | 09/08/1999 | Architectural | Structural |
| 7 | Project Name: Office Building\Building: Offices\Floor: First\Space: Conference room\Architectural\Window: W03 node/branch is added | 09/07/1999 | Architectural | Structural |
| 8 | Project Name: Office Building\Building: Offices\Floor: First\Arch_Level is proposed to be changed from +3.10 m to +3.25 m. (Ref. Proposed chang | 09/08/1999 | Architectural | Structural |

Criteria:

Changes sent on:

Changes sent by: Architectural

Affecting: Structural

● Applied changes

○ Proposed changes

Fig. 5.23. An Example of a Changes Report.

## 5.7 Modified Design Process

Using the proposed system in a design office will require some changes to the traditional design process. The system can be used in two possible ways. One way is to use the system by a representative (team coordinator) of each team, in addition to the design administrator, to frequently update the BPH of a project according to the designs made by his team members. Part of the changes that might be necessary to facilitate this use of the system is to provide individual designers with a form in which they specify all the changes they made to any component (Fig. 5.24). The team coordinator in each discipline (with the help of the chief designer) can then collect these forms daily from his team members and, accordingly, update the BPH. Also, he can assign any of his team members to respond to any changes received through the system by his discipline. The benefit of this type of use is that the traditional design process followed by individual designers will not change much, thus, causing minimum disruption to designers' work habits.

**Project Name:** ____________________ **Building:** ________________
**Discipline:** ________________________ **Designer:** ________________ **Date:** __________

| No. | Component | Location | Old Value | New Value | Note | Change Type | |
|---|---|---|---|---|---|---|---|
| | | | | | | Proposed | Applied |
| 1 | Length | First floor/Conference room | 430 cm | 450 cm | ---- | ✓ | |
| 2 | ....... | ....... | ....... | ....... | ....... | | |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | | |
| n | ....... | ....... | ....... | ....... | ....... | | |

Fig. 5.24. Daily Changes Form.

The second possible way of using the proposed system is to allow all designers have access to client machines and individual access to the BPH of a project. While high level of coordination can be achieved in this manner, some training and familiarity with the system may be required from all designers. The collaboration tools of the system, in this case, can be used not only at the individual team level but also at the interdisciplinary level as well.

## 5.8 Conclusion

In this chapter a collaborative system that uses recent advances in information technology and computer applications is presented in order to facilitate collaboration, improve coordination, and increase productivity in the design of building projects. The proposed system can be used to store building information, record design rationale, and effectively manage the multidisciplinary design changes in a collaborative environment. The main parts of the proposed system were discussed and a case study was presented. The proposed system is expected to help design firms produce quality designs with less time, cost, and rework. Perceived benefits are expected to be improved design, higher consistency, increased productivity, and better constructability of projects. While the system has been demonstrated to work well in simulated design environment, the next step is to use it in a real-life case study, which is presented in the following chapter (Chapter 6).

# Chapter 6

# Model Evaluation: A Case Study

## 6.1 Introduction

In addition to the design examples discussed in Chapters 4 and 5, this chapter presents a real-world case study project to evaluate the system. The evaluation process was carried out by inviting a number of academic and external design experts to get their evaluation and feedback. The external designers were selected from the firm that designed the case study project as they are familiar with the practical aspects of the design in general and the details of this project in particular.

## 6.2 Case Study Data

A real-world case study was selected to evaluate the system and demonstrate its benefits over current professional practice. The case study is a two-story residential building that is part of a multi-million project designed for a Saudi Prince by a well-recognized and reputable design firm in Saudi Arabia. In spite of its location outside of North America, it employs experts from diverse nationalities and uses the North

American codes and procedures for design and project management. The firm has its own independent design teams for architectural, structural, mechanical, and electrical disciplines. The design firm provided a complete set of documents for the project including the specifications and CAD drawings for the architectural, structural, HVAC, plumbing, and electrical designs. A building was selected from this project due to the availability of the changes made to it during the detailed design stage. For confidentiality reasons, the name of the firm and the project's name were removed from all drawings used in this research.

As shown in Fig. 6.1, the ground floor of the building consists of a living room, a dining room, a bathroom, a kitchen, and a sitting room in addition to circulation areas. The first floor, on the other hand, includes two typical bedroom suites with a recreation hall in between (Fig. 6.2). Each suite includes one bedroom, a sitting area, a bathroom, and a dressing room. The structure of this building was designed using reinforced concrete joist- and waffle-slabs system supported by reinforced concrete beams and columns (Fig. 6.3). The actual changes that took place during the detailed design phase of this building were provided by the design firm. A list of these changes is shown in Table 6.1.

During the discussions with the project's architect, who was also responsible for the coordination work, he noted that change number 10 (removing columns C-23 at axis F-5 and C-24 at axis F-7) was requested by the client to provide free space in the main entrance hall and the recreation area (Fig. 6.4). This change, however, was rejected by the structural engineer who considered it as a major change and requires extensive

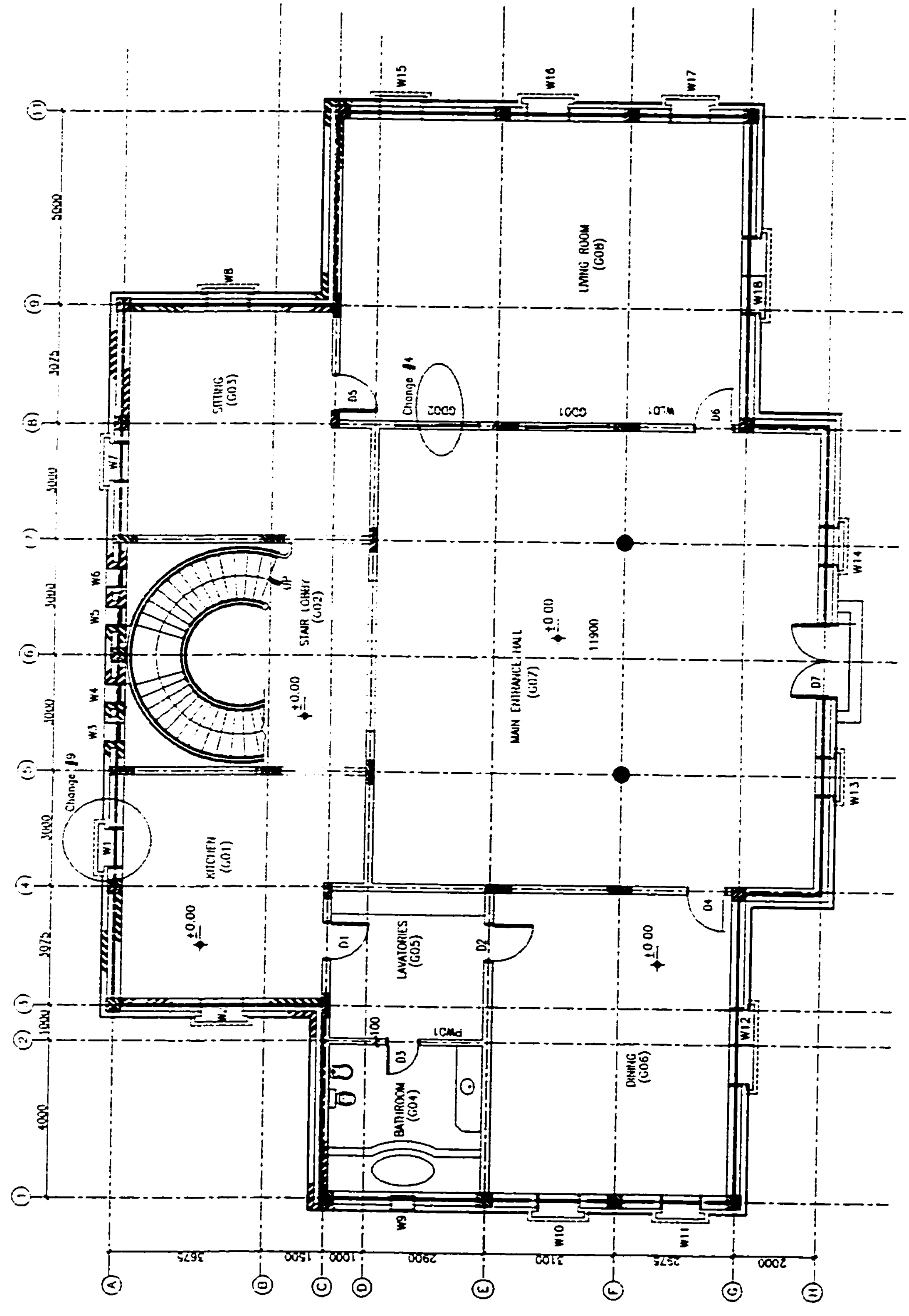


**Fig. 6.1. Ground Floor Architectural Plan of the Case Study Building.**

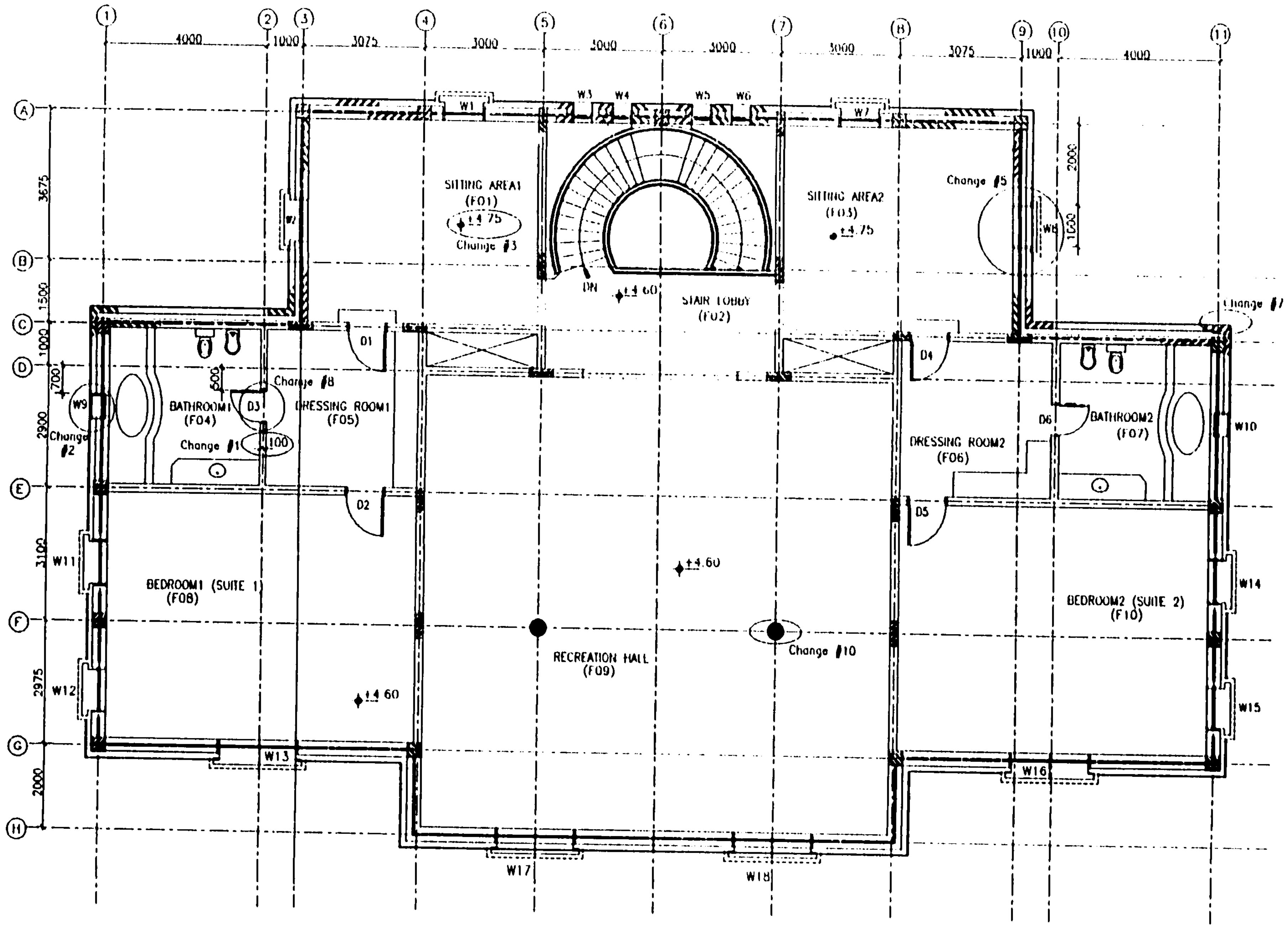


Fig. 6.2. First Floor Architectural Plan of the Case Study Building.

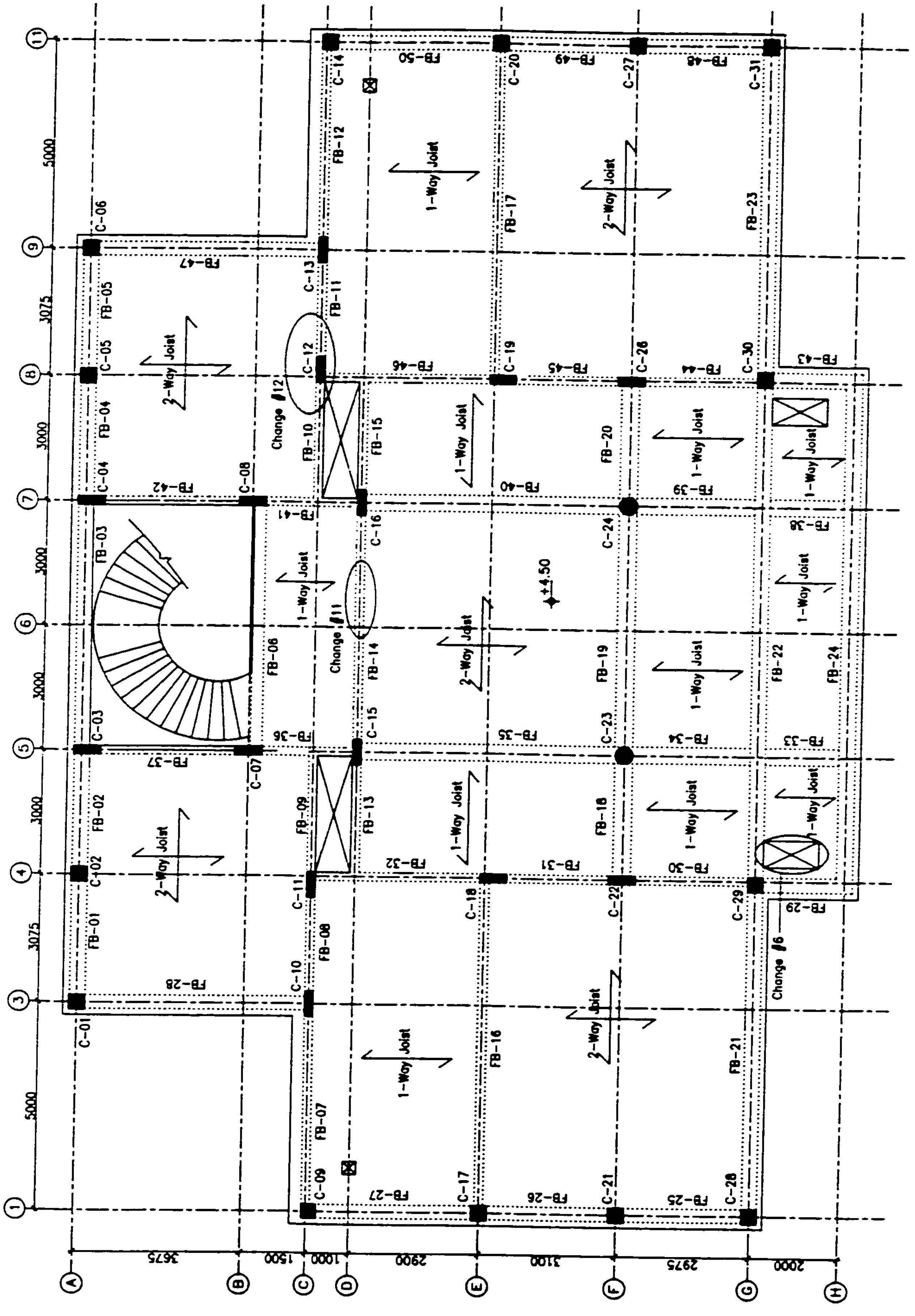
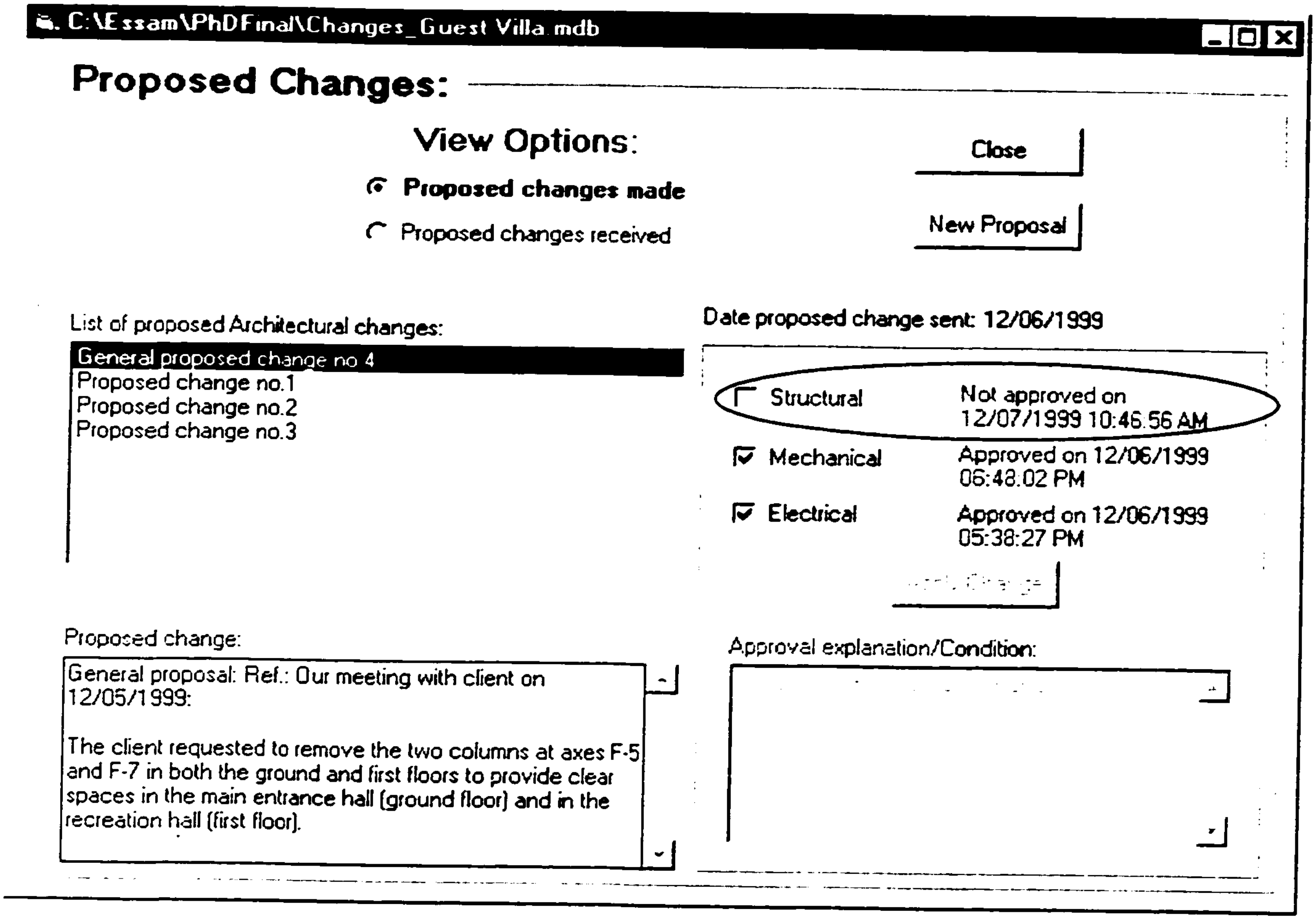


Fig. 6.3. First Floor Structural Framing Plan of the Case Study Building.

**Table 6.1. A List of Actual Changes Made to the Case Study Building.**

| No. | Change | Change by | Location |
|---|---|---|---|
| 1 | The thickness of the partition block walls between the bathroom and lavatories in the ground floor and between the bathrooms and dressing rooms in the first floor were changed from (15 cm) to (10 cm) | Architect | Ground floor and first floor |
| 2 | Widths of all bathroom windows are increased from (50 cm) to (65 cm) | Architect | Ground floor and first floor |
| 3 | The levels of the sitting areas are changed from (+4.60 m) to (+4.75 m) | Architect | First floor |
| 4 | Two Aluminum/Glass doors (width=200 cm) are added in the wall at axis 8 between axes D and F | Architect | Ground floor |
| 5 | Except the bathroom window, change the widths of all the windows at axes 9 and 11 from (100 cm) to (200 cm) to provide more view to the swimming pool area. | Architect | Ground floor and first floor |
| 6 | Mechanical openings in slabs were introduced between axes G-H and 4-5 and between axes G-H and 7-8. | Mechanical | First floor |
| 7 | To reduce cost, external stone cladding was removed and replaced with paint. | Architect | All external facade |
| 8 | Door-widths of all bathrooms were changed from (100 cm) to (90 cm). | Architect | Ground floor and first floor |
| 9 | The kitchen window at axis A was deleted to provide more space for cabinets | Architect | Ground floor |
| 10 | Remove the two columns at axes F-5 and F-7. | Architect | Ground floor and first floor |
| 11 | The depths of beams at axis D between axes 5 and 7 are increased by 20 cm. | Structural | First floor and roof |
| 12 | Depths of columns (C-11) at axis C-4 and (C-12) at axis C-8 are changed from 40 cm to 50 cm | Structural | Ground floor and first floor |



**Proposed Changes:**

**View Options:**

● **Proposed changes made**

○ Proposed changes received

List of proposed Architectural changes:

- General proposed change no 4
- Proposed change no.1
- Proposed change no.2
- Proposed change no.3

Date proposed change sent: 12/06/1999

| | |
|---|---|
| ☐ Structural | Not approved on 12/07/1999 10:46:56 AM |
| ☑ Mechanical | Approved on 12/06/1999 06:48:02 PM |
| ☑ Electrical | Approved on 12/06/1999 05:38:27 PM |

Proposed change:

General proposal: Ref.: Our meeting with client on 12/05/1999:

The client requested to remove the two columns at axes F-5 and F-7 in both the ground and first floors to provide clear spaces in the main entrance hall (ground floor) and in the recreation hall (first floor).

Approval explanation/Condition:

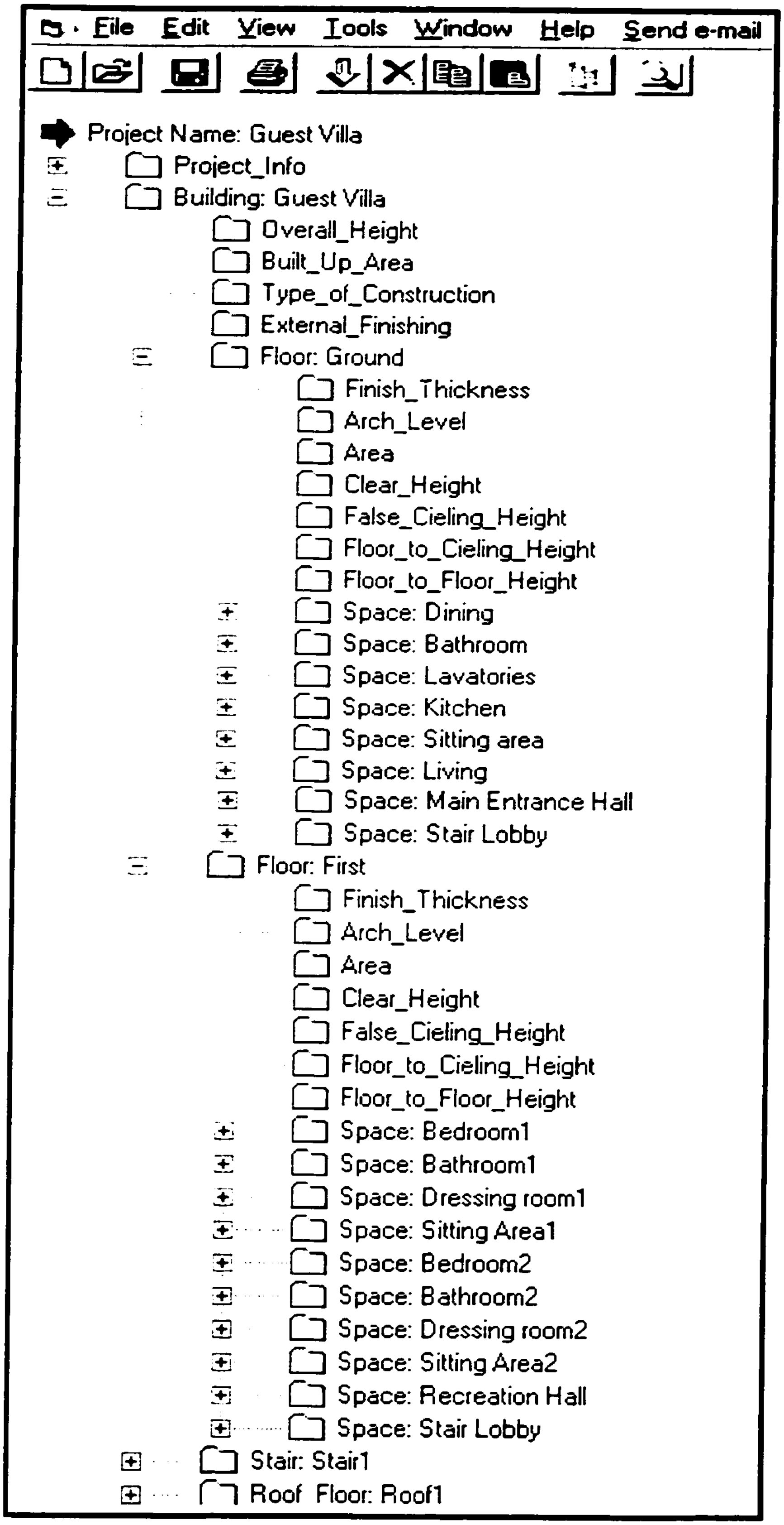
Fig. 6.4. The Change Proposal Rejected by the Structural Engineer.

redesign work. This change, therefore, was not applied and the two columns were not removed and remained unchanged. It should also be noted that the last two changes (shown shaded in Table 6.1) were not provided by the firm. After noticing contradictions between some of the architectural and structural drawings, the author, who was a former employee in the firm, informed the project's architect who, in turn, called the structural engineer for a meeting to discuss this matter. It was concluded from the meeting that these two changes were made by the structural engineer who did not inform the architect with these changes, considering them insignificant.

More details about the changes listed in Table 6.1 and the actual problems encountered during the negotiations for and implementation of some of these changes are discussed in the following section. The following section also explains how the proposed system helped in reducing most of these problems.

## 6.3 Implementing the Case Study

The four independent design disciplines for architectural, structural, mechanical, and electrical, were involved in the design of the building components for this project. Using the proposed system, a new BPH for the building was created on the server machine by only specifying the number of floors in the building and the number of spaces in each floor. An initial BPH for this building was automatically generated using default components from the BCL. The default names of the components were then changed by the architect to reflect the actual names of the building's floors and spaces (Fig. 6.5). As shown in the figure, the generated BPH includes the ground floor and first floor spaces with default stair and roof components automatically added from the BCL to the BPH. The structural components of the building were also input easily on the client machine. To further refine the initial BPH as per the detailed project information, all design participants can use the BCL to add new components to the BPH. Fig. 6.6 shows an example of a new "Door" component added by the architect under the "Living Room" space of the "Ground Floor". Fig. 6.7, on the other hand, shows some of the structural components generated for the "Sitting Area2" space in the "First Floor" of the building. Using the BCL, all design disciplines started creating their BPHs under each



- Project Name: Guest Villa
  - Project_Info
  - Building: Guest Villa
    - Overall_Height
    - Built_Up_Area
    - Type_of_Construction
    - External_Finishing
    - Floor: Ground
      - Finish_Thickness
      - Arch_Level
      - Area
      - Clear_Height
      - False_Cieling_Height
      - Floor_to_Cieling_Height
      - Floor_to_Floor_Height
      - Space: Dining
      - Space: Bathroom
      - Space: Lavatories
      - Space: Kitchen
      - Space: Sitting area
      - Space: Living
      - Space: Main Entrance Hall
      - Space: Stair Lobby
    - Floor: First
      - Finish_Thickness
      - Arch_Level
      - Area
      - Clear_Height
      - False_Cieling_Height
      - Floor_to_Cieling_Height
      - Floor_to_Floor_Height
      - Space: Bedroom1
      - Space: Bathroom1
      - Space: Dressing room1
      - Space: Sitting Area1
      - Space: Bedroom2
      - Space: Bathroom2
      - Space: Dressing room2
      - Space: Sitting Area2
      - Space: Recreation Hall
      - Space: Stair Lobby
    - Stair: Stair1
    - Roof Floor: Roof1

**Fig. 6.5. Part of the BPH of the Case Study Building.**

space in the BPH. As discussed under sections 5.5.6 and 5.5.7 (Chapter 5), the default options at this stage were set to "lock send changes" and use the "non-approval process". As such, each new component added to the BPH was not considered as a change and, therefore, was not communicated to affected parties. At later stages, however, modifying component values should be done using the "approval process" and can not be done directly from the BPH.

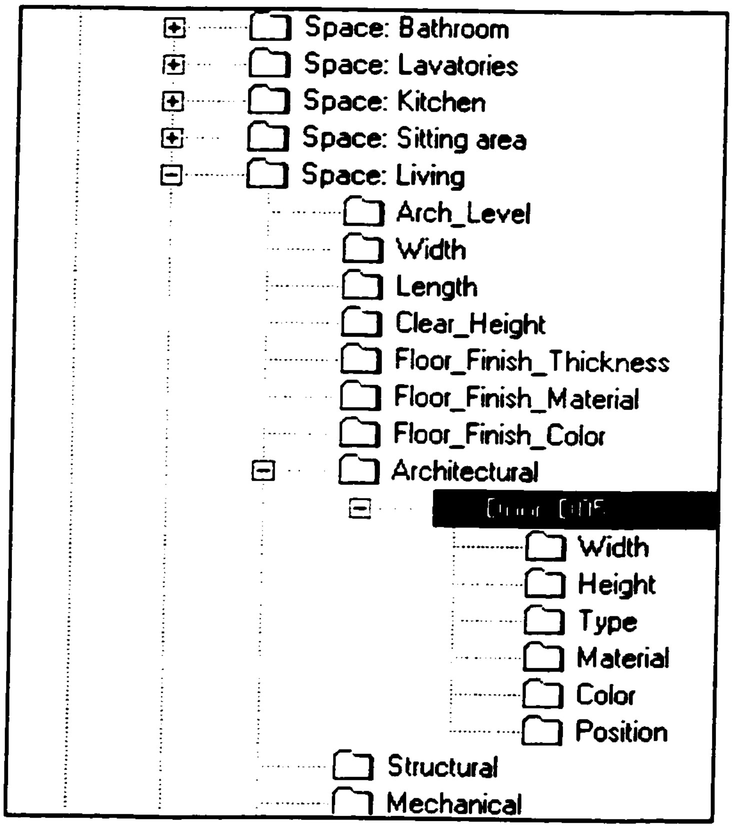
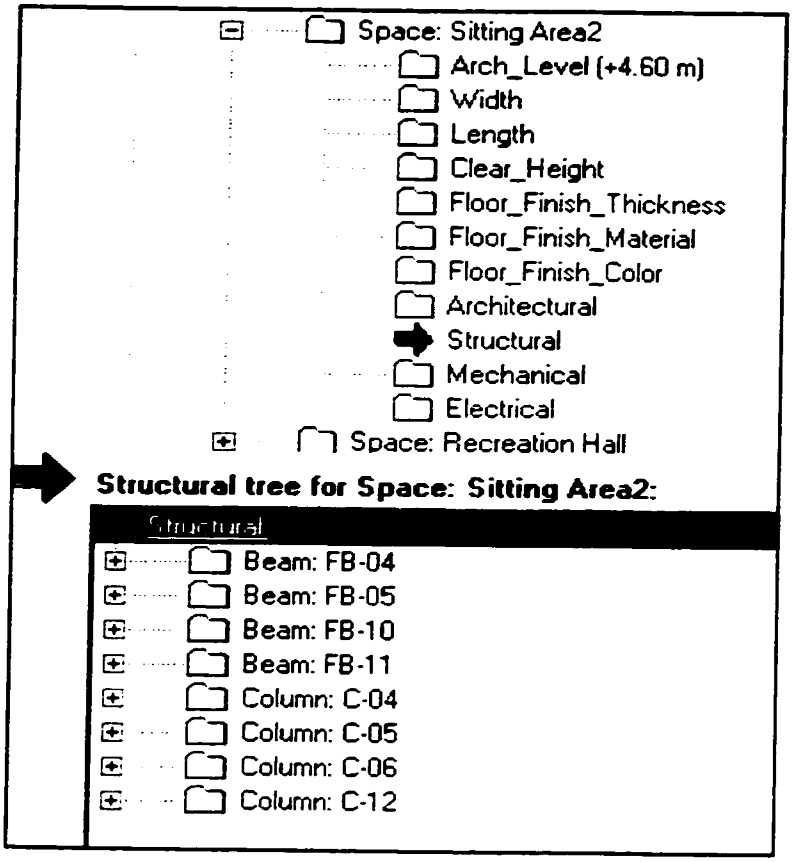


Fig. 6.6. A New "Door" Component Added to the "Living Room" Space.



Space: Sitting Area2
  Arch_Level (+4.60 m)
  Width
  Length
  Clear_Height
  Floor_Finish_Thickness
  Floor_Finish_Material
  Floor_Finish_Color
  Architectural
  Structural
  Mechanical
  Electrical
Space: Recreation Hall

**Structural tree for Space: Sitting Area2:**

Structural
Beam: FB-04
Beam: FB-05
Beam: FB-10
Beam: FB-11
Column: C-04
Column: C-05
Column: C-06
Column: C-12

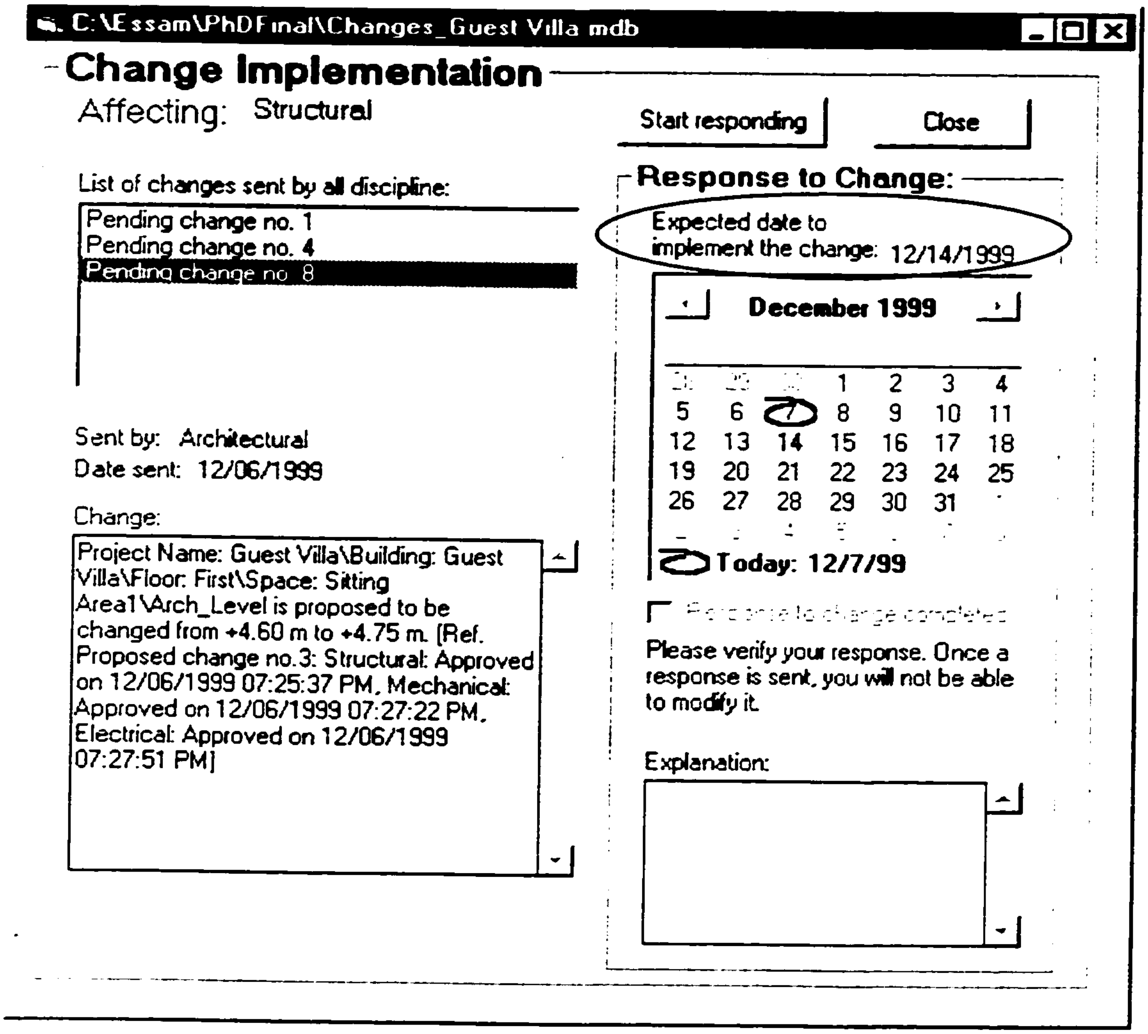
Fig. 6.7. Some of the Structural Components for the "Sitting Area2" Space.

As shown in the list of Table 6.1, several changes were introduced by different design disciplines. The list of all changed components was prepared as shown in the daily changes form of Table 6.2. To illustrate the effectiveness of the proposed system, the first three changes proposed by the architect are considered in this chapter. All the changes proposed by the architect were stored in the "proposed changes" database along with all affected parties and the default design rationale assigned for the changed components (Appendix B). According to the default communication paths, all affected parties instantly received the architect's three proposed changes. The structural

Table 6.2. **A Daily Changes Form Showing A Summary of Changed Components.**

| No. | Component | Location | Old Value | New Value | Note | Change Type | |
|---|---|---|---|---|---|---|---|
| | | | | | | Proposed | Applied |
| 1 | Partition block wall thickness | Ground and first floors | 15 cm | 10 cm | ----- | | |
| 2 | Bathroom window width | Ground floor | 50 cm | 65 cm | ----- | | |
| 3 | Sitting area Level | First Floor | +4.60 m | +4.75 m | ----- | | |
| 4 | Door | Ground floor | ----- | ----- | Added | | |
| 5 | Window width | Ground and first floors | 100 cm | 200 cm | ----- | | |
| 6 | Mechanical opening | First Floor | ----- | ----- | Added | | |
| 7 | External stone cladding | All external facade | ----- | ----- | Deleted | | |
| 8 | Door width | Ground and first floors | 100 cm | 90 cm | ----- | | |
| 9 | Window | Ground floor | ----- | ----- | Deleted | | |
| 10 | Column | Ground and first floors | ----- | ----- | Deleted | | |
| 11 | Beam depth | First and roof floors | ----- | ----- | Increased by 20 cm | | |
| 12 | Column depth | Ground & first floors | 40 cm | 50 cm | ----- | | |

engineer, for example, received the three change-proposals sent by the architect and responded to them (Appendix C). Also, the structural engineer, among others, received the components that can be influenced by these change-proposals (i.e., the default design rationale). As illustrated in Fig. B2 (Appendix B) and Fig. D2 (Appendix D), the structural engineer was notified with the components that may be affected by change-proposal number 2 (changing the bathroom window width from 50 cm to 65 cm). All affected parties approved these change proposals and, accordingly, the architect was instantly notified of their responses including their approval dates and any explanation accompanying these approvals. After getting the approvals of all affected parties, the architect applied these changes and, accordingly, the values of the changed components were replaced with their new values. The structural engineer, who approved the three change proposals, informed the architect that change proposal number 3 will require him to make many modifications in his design. This is because this change requires the level of all beams along axes A, C, 3, 5, 7, and 9 to be changed. As a result of this change, the continuity of these beams was changed and a redesign was, therefore, necessary. A redesign of the slabs around the first floor sitting areas was also necessary. Accordingly, the structural engineer set a time to complete these modifications in his design and calculations (Fig. 6.8). Mechanical and electrical disciplines were also affected by changes and modified there designs accordingly. The system tracks the responses made by affected parties (including structural) to all applied changes and uses its warning system to remind them of pending changes. If the structural engineer, for example, could not complete the modifications in his design on the time specified in the screen capture of Fig. 6.8, he will receive a warning message until he completes this pending job. Other applied changes that need to be implemented by the structural engineer are shown in Appendix D. Using the powerful capabilities of the warning system, the administrator was able to track and follow up on all proposed and applied changes and make sure that affected parties respond to them. As discussed earlier in this chapter, the structural engineer considered changes 11 and 12 (shown shaded in Table 6.1) as insignificant and made these changes without notifying



**Change Implementation**

Affecting: Structural

List of changes sent by all discipline:
Pending change no. 1
Pending change no. 4
Pending change no. 8

Sent by: Architectural
Date sent: 12/06/1999

Change:
Project Name: Guest Villa\Building: Guest Villa\Floor: First\Space: Sitting Area1\Arch_Level is proposed to be changed from +4.60 m to +4.75 m. [Ref. Proposed change no.3: Structural: Approved on 12/06/1999 07:25:37 PM, Mechanical: Approved on 12/06/1999 07:27:22 PM, Electrical: Approved on 12/06/1999 07:27:51 PM]

**Response to Change:**

Expected date to implement the change: 12/14/1999

**Today: 12/7/99**

☐ Response to change completed

Please verify your response. Once a response is sent, you will not be able to modify it.

Explanation:

Fig. 6.8. A Time Set by the "Structural" to Implement An Applied Change.

other disciplines. Increasing the depths of the first floor beam FB14 and the roof beam at axis D between axes 5 and 7 resulted in having these beams projecting in the arches below them, which was not acceptable to the architect. On the other hand, changing the depth of column C-12 at axis C-8 from 40 cm to 50 cm caused another problem to the architect. As a result of this change, the column was projecting inside door D5 of the ground floor living room and door D4 of the first floor dressing room. These problems could not happen using the proposed system as the structural engineer will be forced to use the "Approval Process" to make these changes. Using the proposed system, these changes were efficiently communicated to affected parties (including the architect). The structural engineer was allowed to apply these changes only after proposing them and getting the approvals of all affected parties. The architect, who was instantly notified by this change, shifted the two doors (D4 and D5) by 10 cm. It can be noticed from this example that, without the help of the proposed system, these problems may not be discovered until during construction, where changes could be costly and, in many cases, difficult to implement.

The project's architect was very impressed with the overall performance of the system including its ability to solve many of the problems that may have happened using the traditional methods of communicating changes. He also expressed his appreciation regarding the capabilities of the reporting system and asked for a permission to experiment with the system on other real-world projects in the future.

## 6.4 Model Evaluation

Once a prototype of the proposed design collaboration system was developed, an effort was made to evaluate the various components of the system and obtain quick feedback from potential users. An invitation was, therefore, extended to a number of academic and industry professionals to view a live presentation of the system's use on the same case study presented in sections 6.2 and 6.3 of this chapter. The opinion of the attendants was then solicited through a questionnaire (Appendix E) that was filled after the presentation. The questionnaire included a total of 26 questions and is organized into three sections: (1) overall system features; (2) representation of design components; and (3) management of design changes. The attendants were asked to answer each question by providing a score from one (bad/unacceptable) to five (excellent/desirable) to represent their subjective assessment of the usefulness of the system features. As shown in Fig. 6.9, fifty-one responses were received (32 from industry and 19 from academia). The majority of the respondents are from structural, construction, and architectural fields (Fig. 6.10). The respondents provided average scores of 4.42, 4.57, and 4.81 for the three sections of the questionnaire, respectively (Table 6.3). Details of the questionnaire results and the evaluation of the respondents are briefly summarized in Appendix F. The overall average score is 4.53 indicating a very favorable response to the system's performance and capabilities. Three interesting observations are drawn from the responses received (Fig. 6.11). First, while the attractiveness of the system to large design firms was given a high average score of 4.58, the attractiveness of the system to small design firms received the lowest average score (3.52) of all questions. Second, all respondents gave the highest score (4.94) to the automated warning and reporting capabilities. Thirdly, about 70% of the respondents perceived that the proposed system implies noticeable changes to traditional work habits. A discussion regarding the latter issue was presented under the "Modified Design Process" section of Chapter 5. The majority of the respondents expressed their appreciation regarding the effectiveness of the system particularly for managing and communicating design changes and asked for permission to use and experiment with the system on real-world projects.

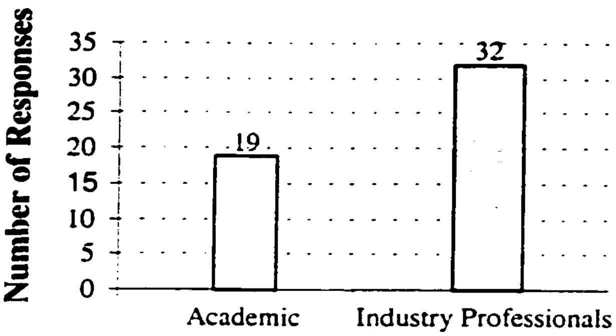


Fig. 6.9. The Questionnaire Responses.

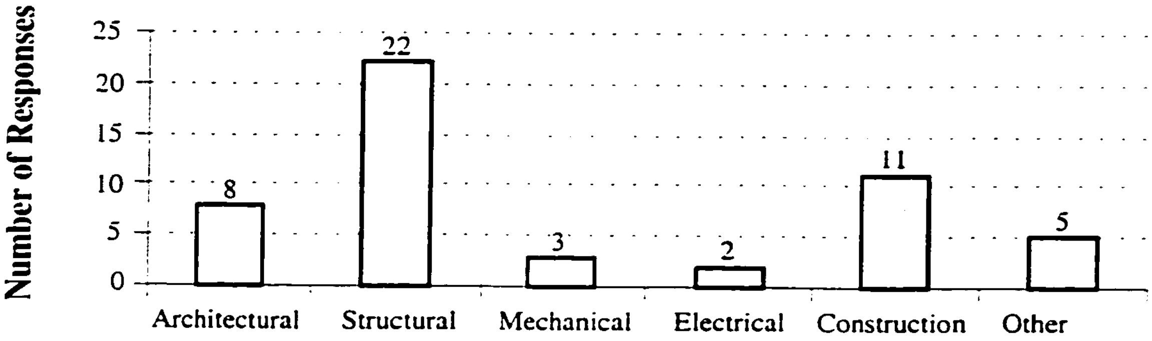


Fig. 6.10. The Specialization of the Questionnaire Respondents.

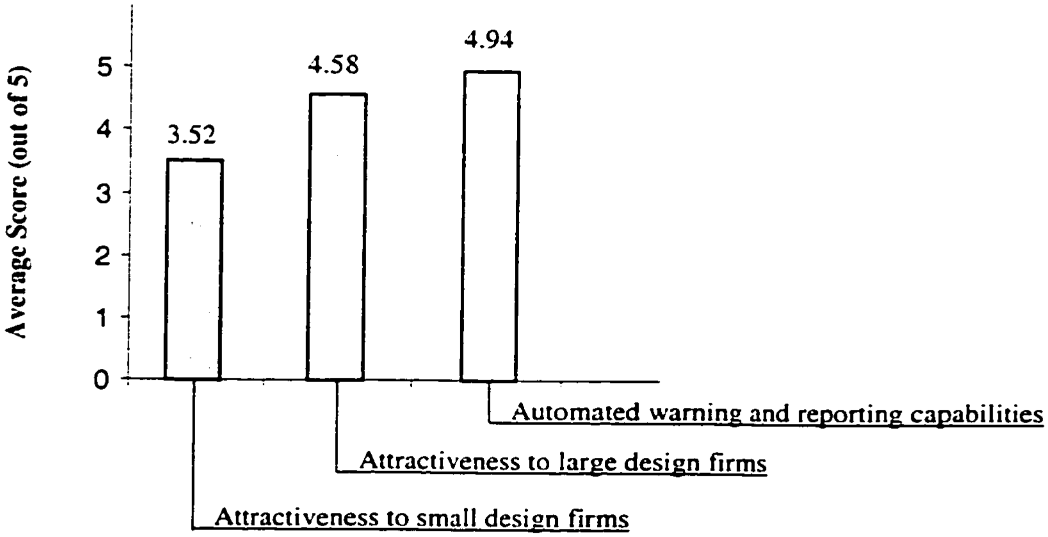


Fig. 6.11. Some Observations from the Questionnaire.

The questionnaire results, as such, are encouraging and reflect the effectiveness of the proposed information model components and the overall usefulness and acceptability of the system. Some of the suggestions made by respondents are to extend the system to include the design and construction stages of projects, to fully implement the system on the world wide web, to involve other parties in the communication paths such as the owner and the quantity surveyor or other specialty groups, to integrate the system with design software systems, and to fully integrate the system with CAD. Some of these suggestions can be considered for future work, as discussed in Chapter 7.

While the adopted evaluation approach provided a quick and useful feedback on important refinements to the system, real-life experimentation with the system is still needed. An effort is currently being carried out in collaboration with a design firm to set up the system on the firm's local area network and experiment with it on an actual project being designed by the firm. This, however, is an additional and long-term validation, which can be considered for future work, as discussed in Chapter 7.

**Table 6.3. The Performance of the Proposed System.**

| Category | Score (out of 5) |
|---|---|
| Overall System Features | 4.42 |
| Representation of Design Components | 4.57 |
| Management of Design Changes | 4.81 |
| Overall Performance | 4.53 |
| Number of respondents | 51 |

## 6.5 Conclusion

In this chapter, a real-world case study project, obtained from a reputable design firm, has been presented to evaluate the system. Some of the actual changes that took place during the detailed design phase of the case study project were discussed. All designers used the proposed system to create a complete BPH for the project using the default components of the BCL. This chapter also summarized the system's powerful capabilities in handling some of the coordination problems that took place during the actual design of the building. The proposed system, as such, helped in organizing the project's data in a structured manner and effectively solved some of the problems that took place during the process of communicating design changes. The evaluation process was then carried out by obtaining the feedback and suggestions of several academic and design experts through a questionnaire. The respondents of the questionnaire provided their assessment regarding the overall performance of the system. It can be concluded from the responses received that the system can be very attractive to large design firms. Also, the questionnaire results reflected the effectiveness of the proposed system in managing design changes and the powerful capabilities of its reporting and automated warning.

# Chapter 7

# Conclusions

## 7.1 Conclusions

In this research, a prototype of a collaborative system for improving design coordination is developed to enable design firms to work more productively and cost effectively. The system uses an information model that is developed to store design information, record design rationale, and effectively manage the multidisciplinary design changes in a collaborative environment. The developed information model uses a central Building Components Library (BCL) to create a complete Building Project Hierarchy (BPH) for a project. The novel aspect of the proposed BPH is its hierarchical representation of the multidisciplinary design data within each building space. Each building component is an active object that encapsulates information related to its default design rationale and its preset communication paths. The design rationale for each component is represented by a description of its desired performance criteria and its dependency relationships with other components. The communication paths help in automatically communicating changes made to any component in the BPH to all affected parties.

In this research, the design administrator was introduced and recommended as a new participant in the design process, particularly in large-size projects. The design administrator works as a dedicated design coordination official, and is mainly responsible for the tracking and following up on all communications among all parties, administering pending changes, and tracking change proposals and applied changes. In addition, the design administrator can help in generating and administrating the BCL, presetting the required communication paths for each component in the BCL, providing his input to the initial design rationale of BCL components, and conducting regular coordination meetings.

Based on the system performance, the apparent advantages of the proposed system over current practice lie in its unified information representation, its efficient change management procedures, and its powerful reporting capabilities. Also, the proposed model has several interesting features and advantages, including the following:

1. It provides a coordination scheme and a documentation for the flow of design information among the various design participants in a project.
2. It includes a building components library (BCL) that functions as a repository of design data needed to describe a complete building project.
3. It incorporates a unified information model to store the multidisciplinary design data of buildings within each space in the form of a building project hierarchy (BPH).
4. It allows the storage of design rationale for all the components in the BPH with their

performance criteria that maintains performance consistency when changes are made to any component.

5. It incorporates a mechanism for design-change management to effectively communicate changes to effected parties, keep track of all changes, and follow up on pending changes. This is expected to provide for effective coordination between design participants, reduce discrepancies, and, therefore, provide a quality design.
6. It integrates items 3, 4, and 5 above in a single effective Internet-based collaborative system. This system facilitates interactions and discussions among remote participants and, therefore, improves communication and coordination. This integration can assist design firms to work more efficiently with less cost and limited resources taking into consideration the current prevailing market pressure and competitive environment.
7. It incorporates a powerful reporting system to help the design administrator follow up on pending changes and track the history of all changes made to a project.
8. It contributes to the office automation efforts and helps the participants in design firms, particularly remote ones, communicate with each other more effectively.

The proposed system was evaluated by applying it on a real-world design project and obtaining the evaluation and feedback of several academic and design experts through a questionnaire. It can be concluded from the responses received that the system can be very attractive to large design firms. Also, the questionnaire results reflected the effectiveness of the proposed system in managing design changes and the powerful capabilities of its reporting and automated warning. The proposed system, as such, can help in organizing projects' data in a structured format and effectively solve many of the coordination problems that are expected to take place during the process of communicating changes in the design of building projects.

## 7.2 Future Research

There are several potential improvements to the design coordination system proposed in this study and other areas of future research related to the developed system. These may include:

- Experimenting with the developed model in actual design firms to report on its performance, suggest improvements, and apply it on more complex real-world design projects.
- Investigating the use of Data-Flow Diagrams (e.g., Abou-Zeid et al. 1995) to examine the flow of the large amount of design data among the diverse participants in the process and, accordingly, refine the design inter-relationships shown in Table 3.5 and Fig. 3.5 (Chapter 3).
- Providing a detailed analysis of the proposed model and its changes to office operations using simulation (Zaneldin et al. 1998, Hegazy et al. 1999). The use of a simulation software (e.g., Process Charter 1995) for process-analysis can identify bottleneck points and help optimize the use of resources. Other benefits of such analysis include the optimum selection of team size, estimation of realistic design time and cost, and the evaluation of the impact of changes in the process. Simulation can

also be used to compare the effectiveness of traditional design procedures versus modified procedures.

- Integrating the proposed model with a document-management solution that is accurate, fast, and reliable. With CAD software becoming one of the basic tools in the design office, files proliferate until projects contain hundreds or thousands of original, secondary, and backup drawings. The perceived benefits of an efficient document-management system include the possible recognition of secured electronic files as legal documents, which facilitates a smooth and effective shift from paper-based procedures.
- Extending the BCL to include a broader list of building components.
- Extending the model to include both the design and construction stages of projects and, therefore, include the contractor as a main party in the communication process.
- Involving other parties in the communication paths such as the owner and the quantity surveyor or other specialty groups.
- Fully implement the model on the World Wide Web to allow designers to collaborate and use the model from remote locations.
- Improve the model by integrating it with the new software. The proposed client/server system can be implemented on machines using Microsoft Office 2000 and can be set up to become completely Internet-based. One of the powerful web features of Microsoft Office 2000 is its web folders. With web folders, it is possible to work with files stored on web servers (rather than LAN servers) and, as such, designers connected to the Internet need no LAN connection to use the system. Also, with Microsoft Office 2000, designers will be able to post database components (tables,

reports, queries) on web pages. The design administrator and designers from all disciplines, for example, can use the web browser to view other project documents (e.g., Bills of quantities) directly.

- Integrating the model with other commercial collaboration tools. HotOffice 2.0 (HotOffice 2.0), for example, is a collaboration tool that can integrate with Microsoft NetMeeting to provide a shared calendar for tracking meetings and tasks. While, at present, all collaboration tools used in the proposed system belong to the Microsoft family of products, it is still possible to take advantage of the latest developments and the new advances in other collaboration tools (Seltzer 1999) by adding them externally to the model.
- Integrating the model with commercially available design software systems.
- Fully integrate the model with CAD Drafting software. As such, building components can be read directly from CAD drawings of each discipline and added to the project's BPH. Also, changed components can be directly modified in CAD drawings.

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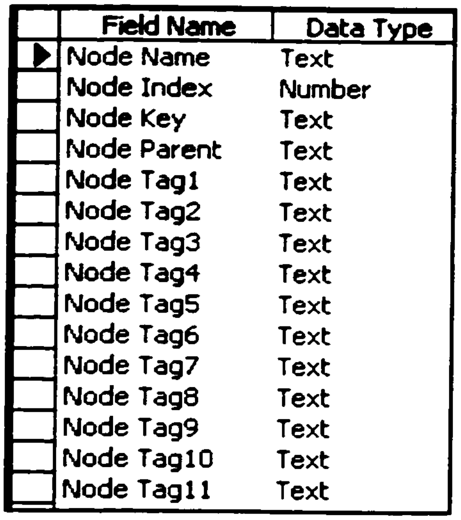
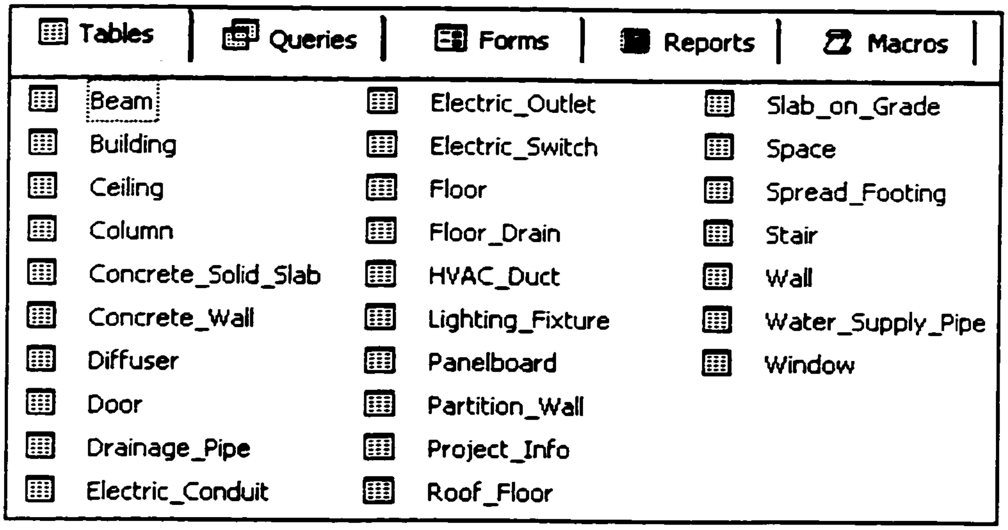
# Appendix A: System Databases.



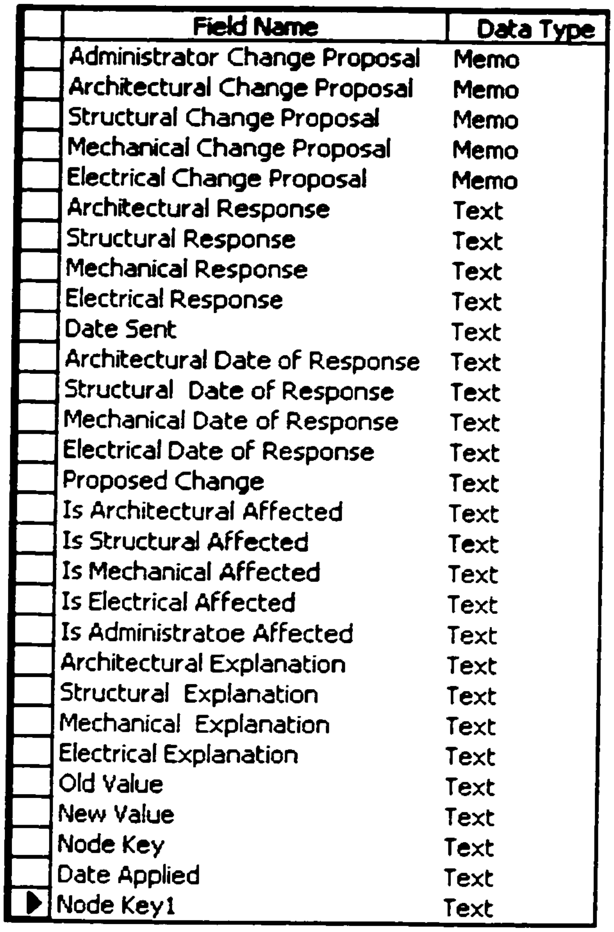
| Field Name | Data Type |
|---|---|
| Node Name | Text |
| Node Index | Number |
| Node Key | Text |
| Node Parent | Text |
| Node Tag1 | Text |
| Node Tag2 | Text |
| Node Tag3 | Text |
| Node Tag4 | Text |
| Node Tag5 | Text |
| Node Tag6 | Text |
| Node Tag7 | Text |
| Node Tag8 | Text |
| Node Tag9 | Text |
| Node Tag10 | Text |
| Node Tag11 | Text |

**Fig. A1. BPH and BCL Databases**



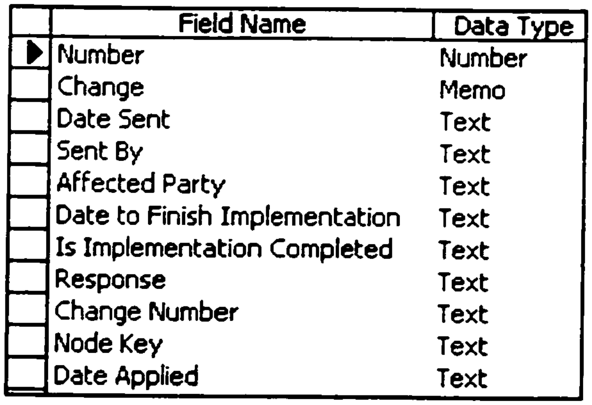
- Beam
- Building
- Ceiling
- Column
- Concrete_Solid_Slab
- Concrete_Wall
- Diffuser
- Door
- Drainage_Pipe
- Electric_Conduit
- Electric_Outlet
- Electric_Switch
- Floor
- Floor_Drain
- HVAC_Duct
- Lighting_Fixture
- Panelboard
- Partition_Wall
- Project_Info
- Roof_Floor
- Slab_on_Grade
- Space
- Spread_Footing
- Stair
- Wall
- Water_Supply_Pipe
- Window

**Fig. A2. BCL Database Tables**



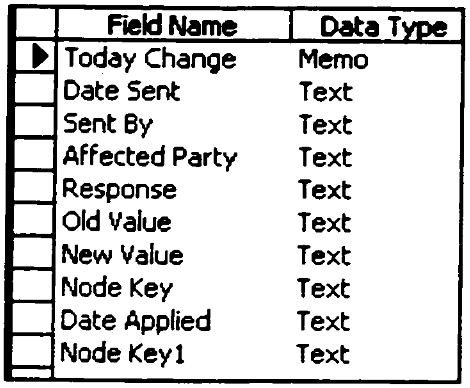
| Field Name | Data Type |
|---|---|
| Administrator Change Proposal | Memo |
| Architectural Change Proposal | Memo |
| Structural Change Proposal | Memo |
| Mechanical Change Proposal | Memo |
| Electrical Change Proposal | Memo |
| Architectural Response | Text |
| Structural Response | Text |
| Mechanical Response | Text |
| Electrical Response | Text |
| Date Sent | Text |
| Architectural Date of Response | Text |
| Structural Date of Response | Text |
| Mechanical Date of Response | Text |
| Electrical Date of Response | Text |
| Proposed Change | Text |
| Is Architectural Affected | Text |
| Is Structural Affected | Text |
| Is Mechanical Affected | Text |
| Is Electrical Affected | Text |
| Is Administratoe Affected | Text |
| Architectural Explanation | Text |
| Structural Explanation | Text |
| Mechanical Explanation | Text |
| Electrical Explanation | Text |
| Old Value | Text |
| New Value | Text |
| Node Key | Text |
| Date Applied | Text |
| Node Key1 | Text |

Fig. A3. Proposed-Changes Database



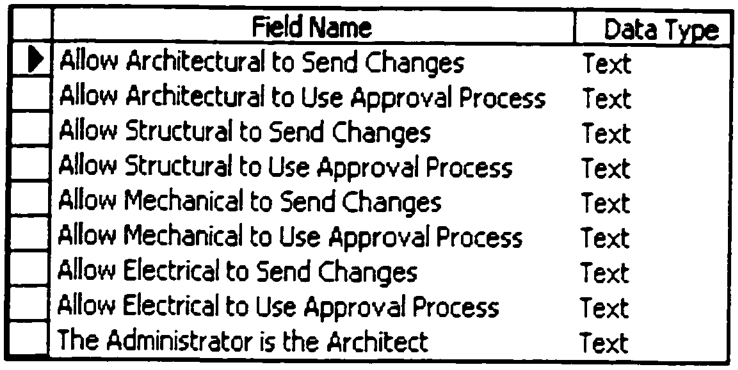
| Field Name | Data Type |
|---|---|
| Number | Number |
| Change | Memo |
| Date Sent | Text |
| Sent By | Text |
| Affected Party | Text |
| Date to Finish Implementation | Text |
| Is Implementation Completed | Text |
| Response | Text |
| Change Number | Text |
| Node Key | Text |
| Date Applied | Text |

Fig. A4. Applied-Changes Database



| Field Name | Data Type |
|---|---|
| Today Change | Memo |
| Date Sent | Text |
| Sent By | Text |
| Affected Party | Text |
| Response | Text |
| Old Value | Text |
| New Value | Text |
| Node Key | Text |
| Date Applied | Text |
| Node Key1 | Text |

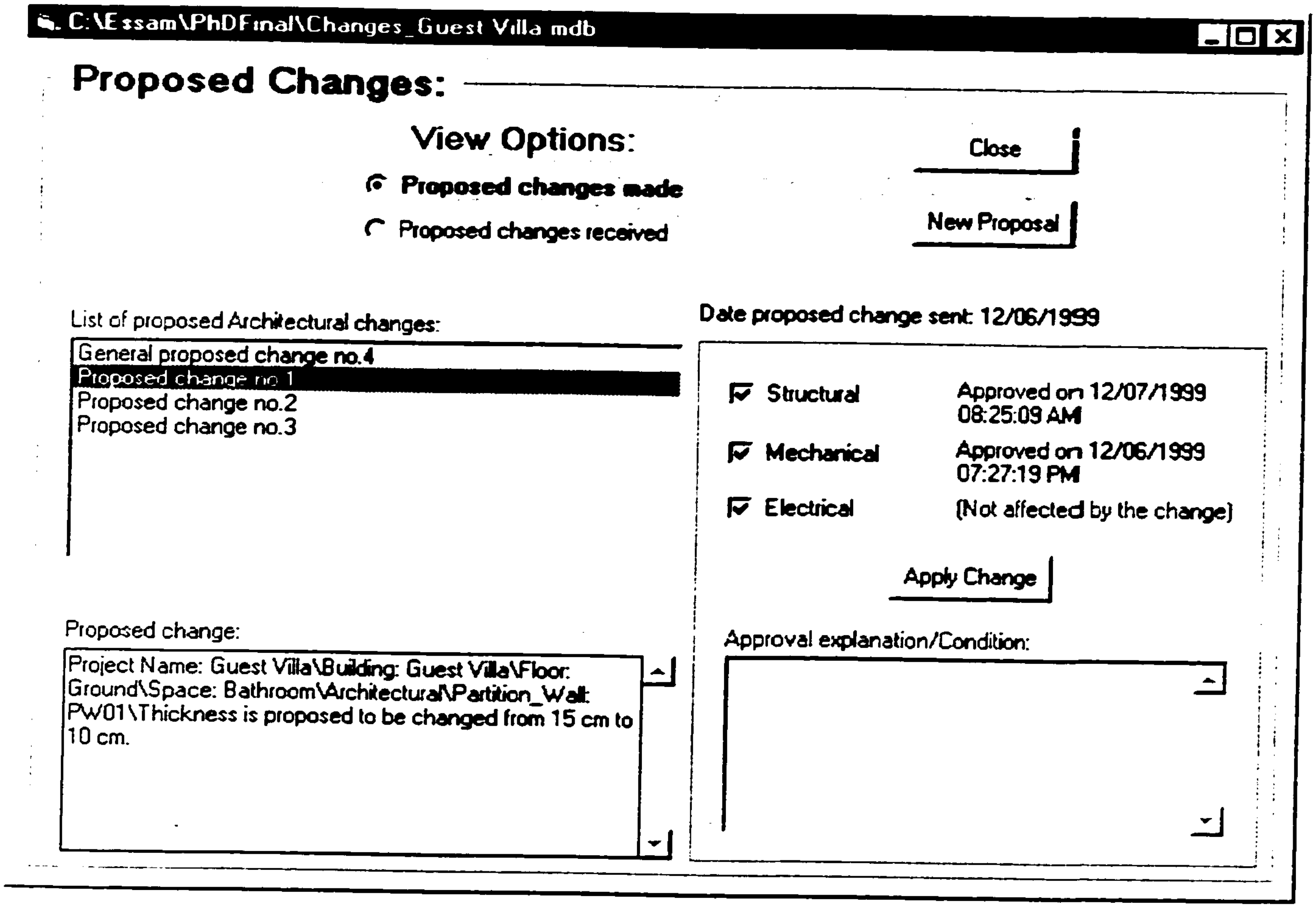
**Fig. A5. Today's-Changes Database**



| Field Name | Data Type |
|---|---|
| Allow Architectural to Send Changes | Text |
| Allow Architectural to Use Approval Process | Text |
| Allow Structural to Send Changes | Text |
| Allow Structural to Use Approval Process | Text |
| Allow Mechanical to Send Changes | Text |
| Allow Mechanical to Use Approval Process | Text |
| Allow Electrical to Send Changes | Text |
| Allow Electrical to Use Approval Process | Text |
| The Administrator is the Architect | Text |

**Fig. A6. The Database of the Options for Managing Design Changes**

## Appendix B: Some of the Changes Proposed by the "Architect" for the Case Study in Chapter 6.



**Proposed Changes:**

**View Options:**

● **Proposed changes made**
○ Proposed changes received

List of proposed Architectural changes:

- General proposed change no.4
- Proposed change no 1
- Proposed change no.2
- Proposed change no.3

Proposed change:

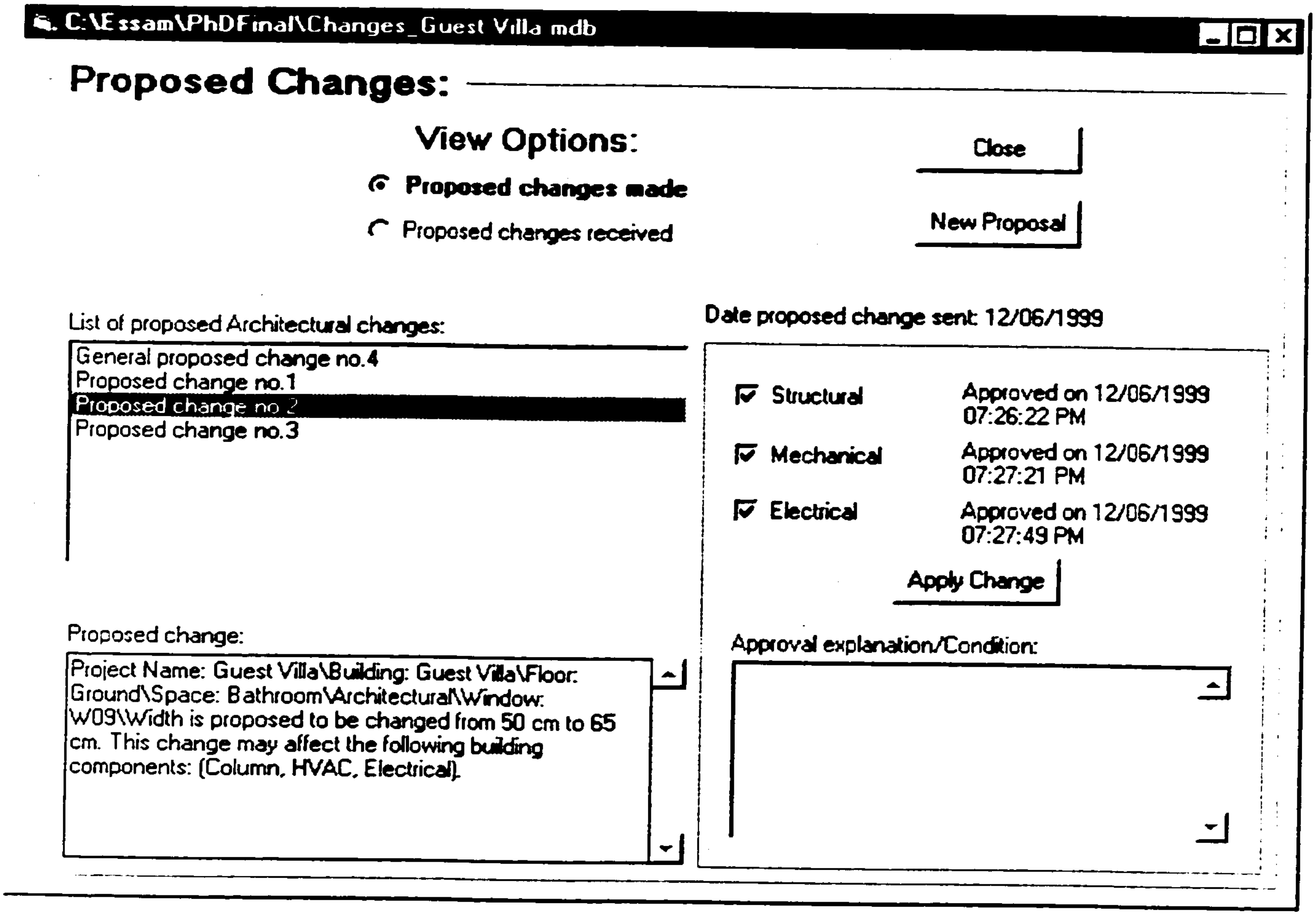
Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Partition_Wall: PW01\Thickness is proposed to be changed from 15 cm to 10 cm.

Date proposed change sent: 12/06/1999

| | |
|---|---|
| ☑ Structural | Approved on 12/07/1999 08:25:09 AM |
| ☑ Mechanical | Approved on 12/06/1999 07:27:19 PM |
| ☑ Electrical | (Not affected by the change) |

Approval explanation/Condition:

Fig. B1. Change-Proposal Number 1.



View Options:

● Proposed changes made

○ Proposed changes received

List of proposed Architectural changes:

- General proposed change no.4
- Proposed change no.1
- Proposed change no.2
- Proposed change no.3

Date proposed change sent: 12/06/1999

☑ Structural Approved on 12/06/1999 07:26:22 PM

☑ Mechanical Approved on 12/06/1999 07:27:21 PM

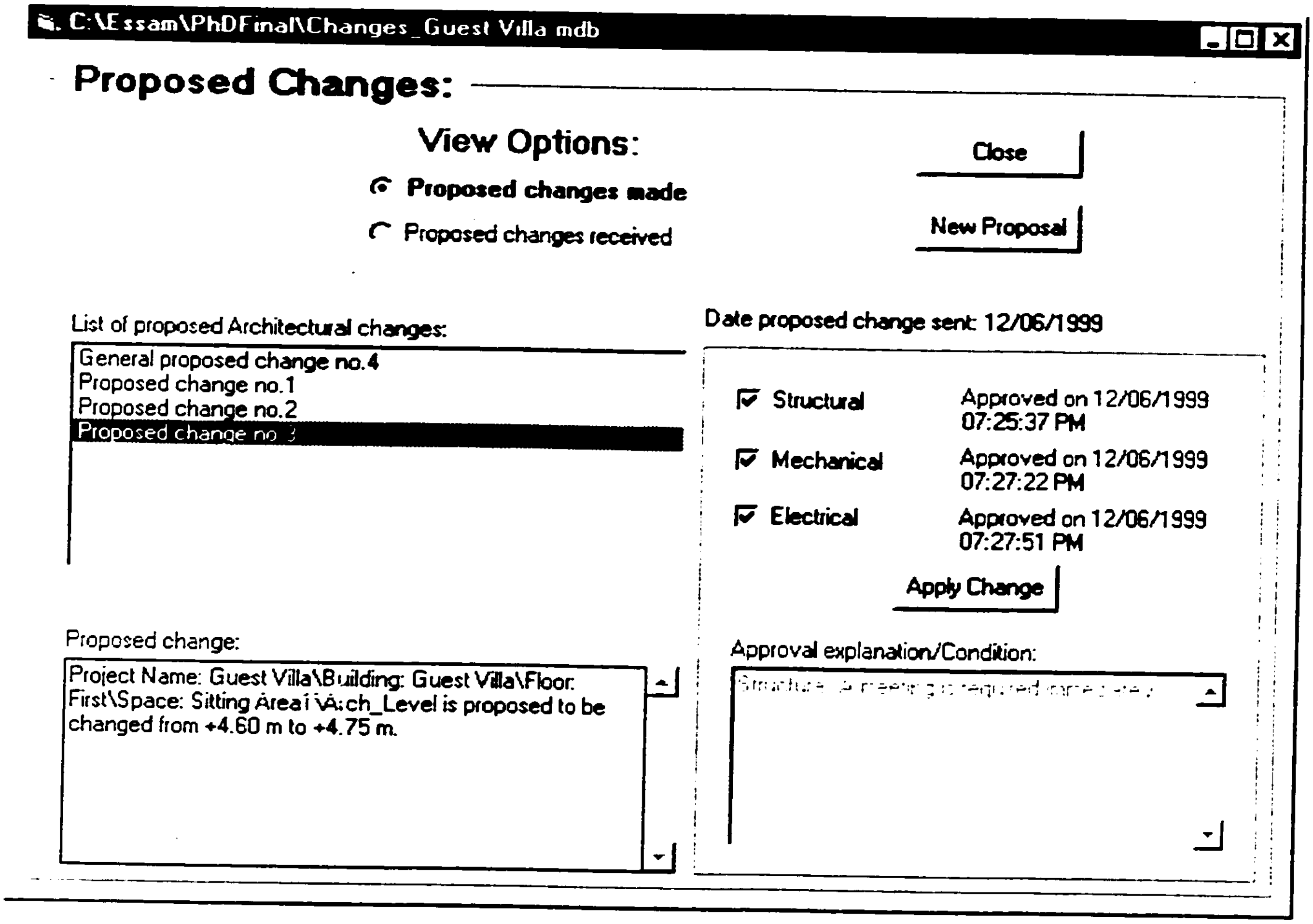
☑ Electrical Approved on 12/06/1999 07:27:49 PM

Proposed change:

Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Window: W09\Width is proposed to be changed from 50 cm to 65 cm. This change may affect the following building components: (Column, HVAC, Electrical).

Approval explanation/Condition:

Fig. B2. Change-Proposal Number 2.



**Proposed Changes:**

**View Options:**

● **Proposed changes made**

○ Proposed changes received

List of proposed Architectural changes:

General proposed change no.4
Proposed change no.1
Proposed change no.2
Proposed change no.3

Date proposed change sent: 12/06/1999

| | |
|---|---|
| ☑ Structural | Approved on 12/06/1999 07:25:37 PM |
| ☑ Mechanical | Approved on 12/06/1999 07:27:22 PM |
| ☑ Electrical | Approved on 12/06/1999 07:27:51 PM |

Proposed change:

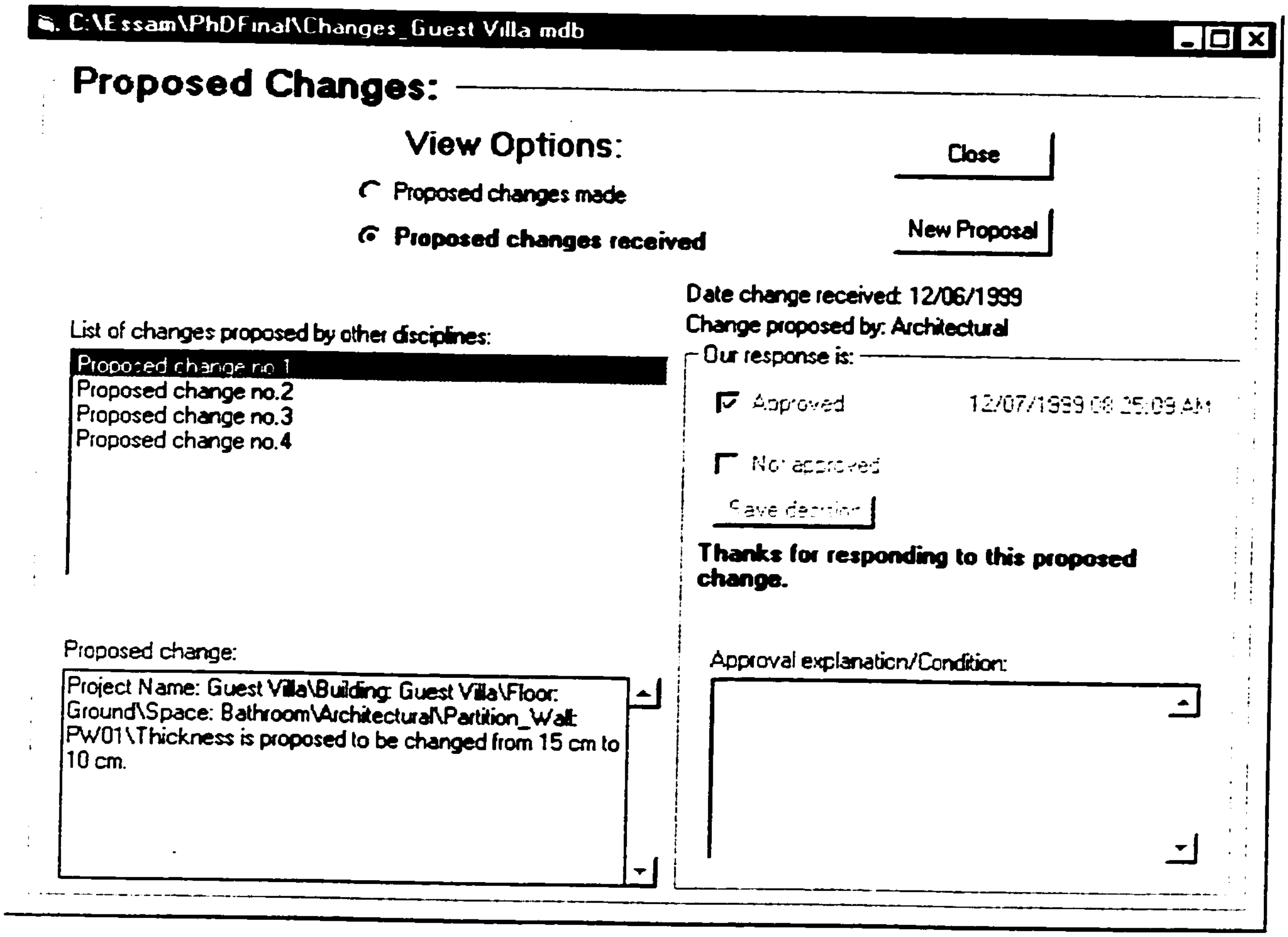
Project Name: Guest Villa\Building: Guest Villa\Floor: First\Space: Sitting Area\Arch_Level is proposed to be changed from +4.60 m to +4.75 m.

Approval explanation/Condition:

Structure: A meeting is required immediately

Fig. B3. Change-Proposal Number 3.

# Appendix C: "Structural" Responses on Some of the Changes Proposed by the "Architect" for the Case Study in Chapter 6.



○ Proposed changes made

● **Proposed changes received**

Date change received: 12/06/1999

Change proposed by: Architectural

List of changes proposed by other disciplines:

- Proposed change no.1
- Proposed change no.2
- Proposed change no.3
- Proposed change no.4

Our response is:

☑ Approved 12/07/1999 08:25:09 AM

☐ Not approved

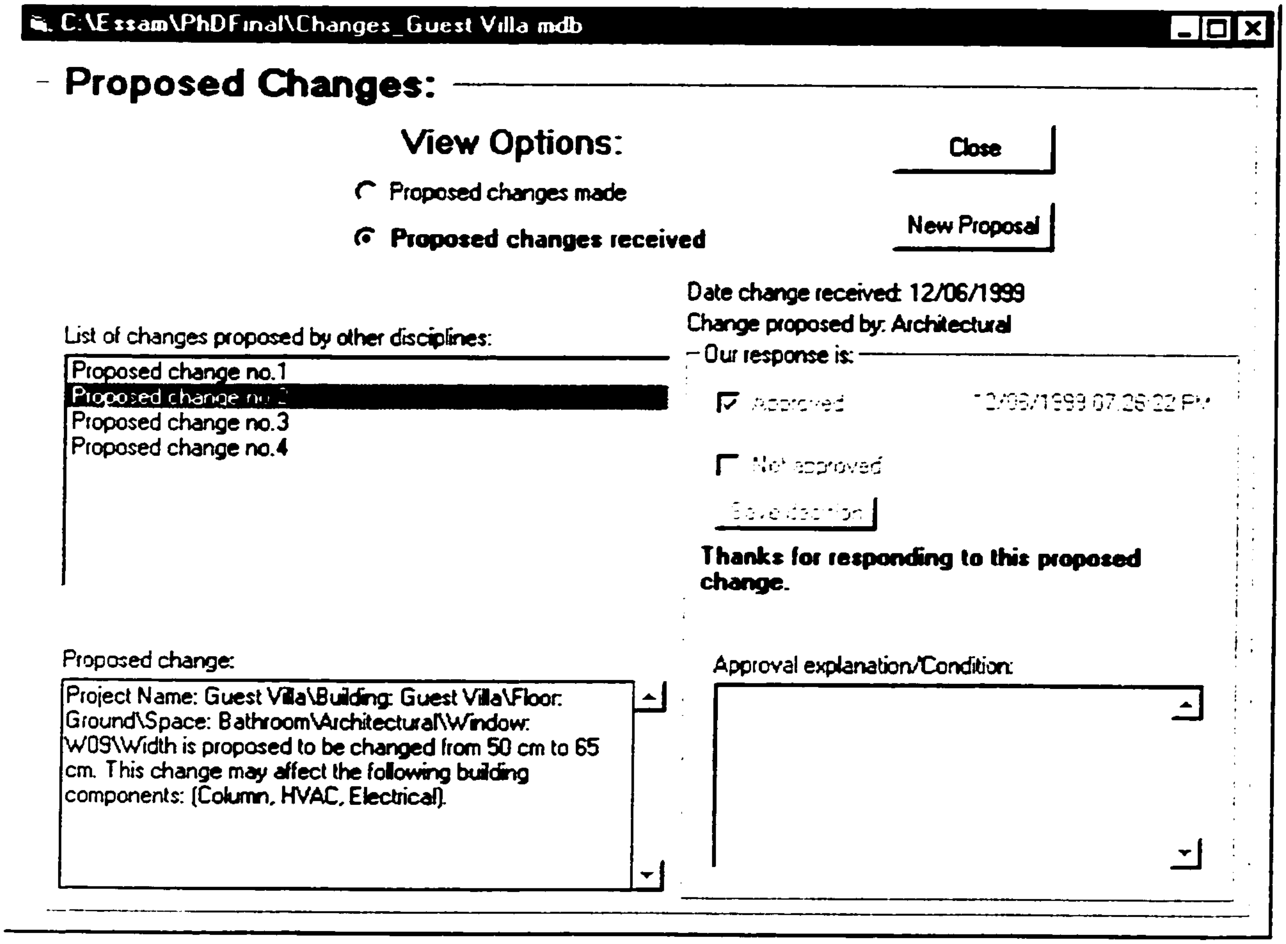
**Thanks for responding to this proposed change.**

Proposed change:

Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Partition_Wall: PW01\Thickness is proposed to be changed from 15 cm to 10 cm.

Approval explanation/Condition:

Fig. C1. Response to Change-Proposal Number 1.



C:\Essam\PhDFinal\Changes_Guest Villa mdb

**Proposed Changes:**

**View Options:**

○ Proposed changes made

● **Proposed changes received**

Date change received: 12/06/1999

Change proposed by: Architectural

List of changes proposed by other disciplines:

Proposed change no.1
Proposed change no.2
Proposed change no.3
Proposed change no.4

Our response is:

☑ Approved 12/06/1999 07:26:22 PM

☐ Not approved

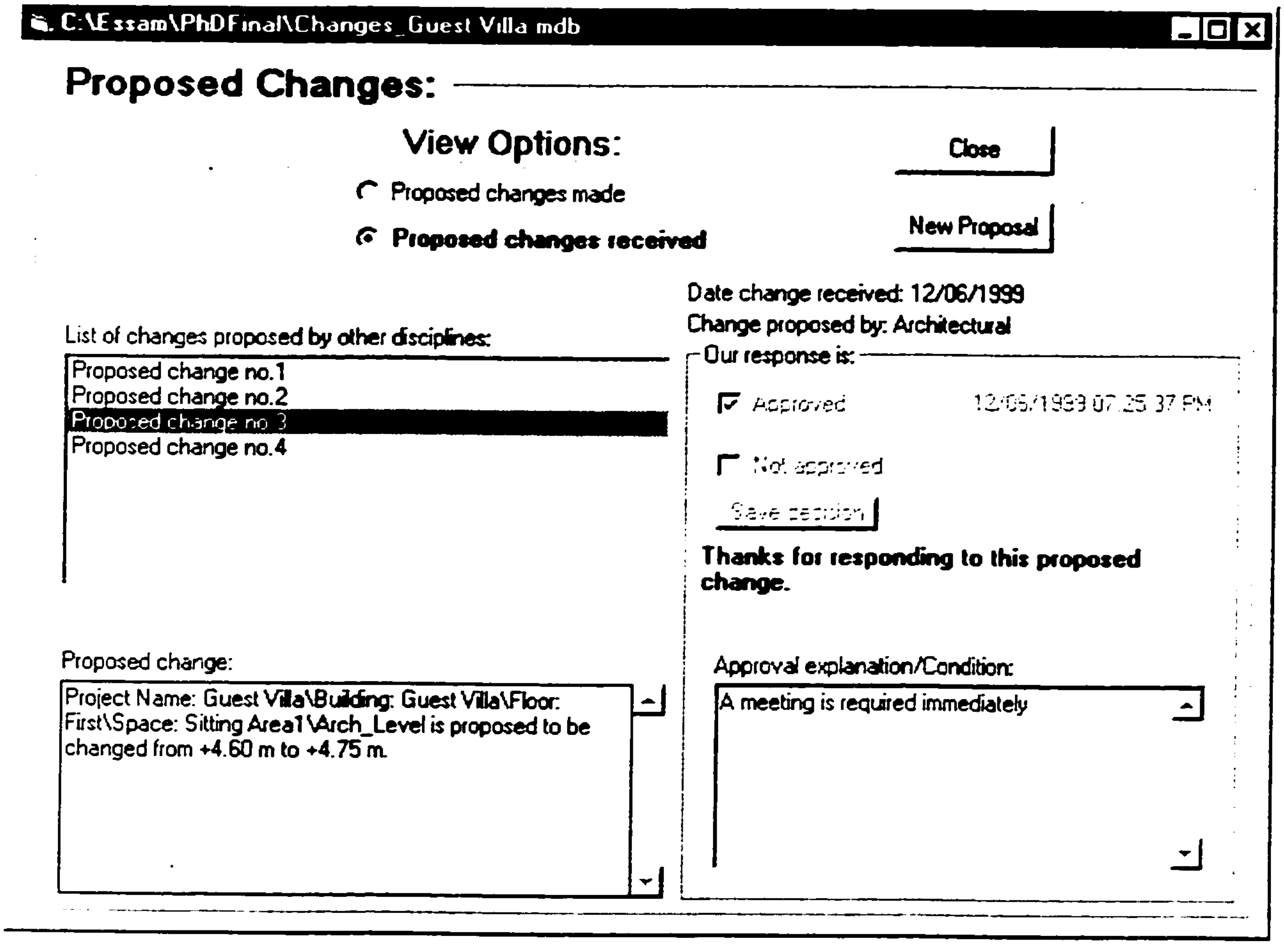
**Thanks for responding to this proposed change.**

Proposed change:

Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Window: W09\Width is proposed to be changed from 50 cm to 65 cm. This change may affect the following building components: (Column, HVAC, Electrical).

Approval explanation/Condition:

**Fig. C2. Response to Change-Proposal Number 2.**



○ Proposed changes made

● **Proposed changes received**

Date change received: 12/06/1999

Change proposed by: Architectural

List of changes proposed by other disciplines:

- Proposed change no.1
- Proposed change no.2
- Proposed change no.3
- Proposed change no.4

Our response is:

☑ Approved 12/06/1999 07:25:37 PM

☐ Not approved

**Thanks for responding to this proposed change.**

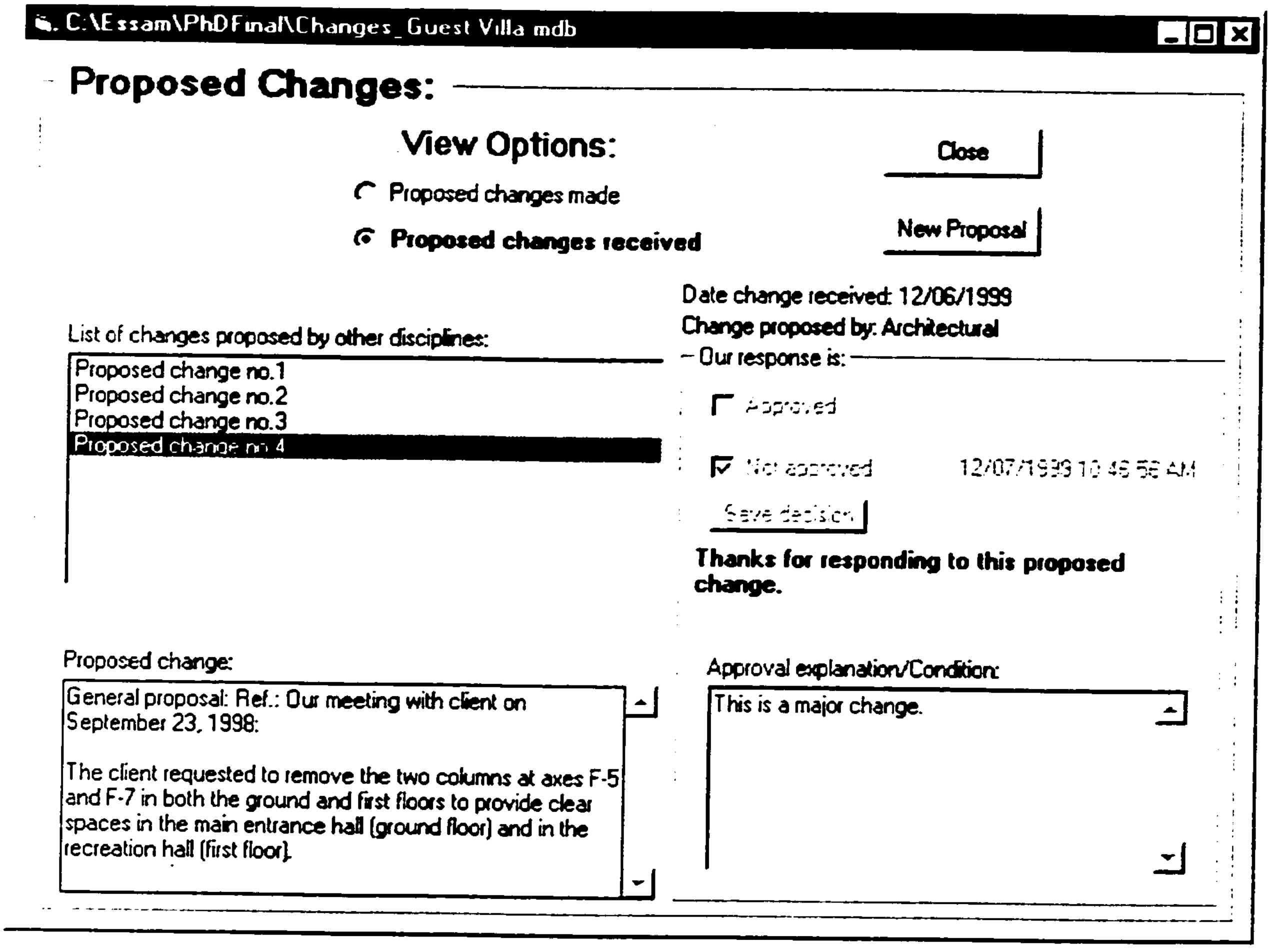
Proposed change:

Project Name: Guest Villa\Building: Guest Villa\Floor: First\Space: Sitting Area1\Arch_Level is proposed to be changed from +4.60 m to +4.75 m.

Approval explanation/Condition:

A meeting is required immediately

**Fig. C3. Response to Change-Proposal Number 3.**



**Proposed Changes:**

**View Options:**

○ Proposed changes made

● **Proposed changes received**

Date change received: 12/06/1999

Change proposed by: Architectural

List of changes proposed by other disciplines:

- Proposed change no.1
- Proposed change no.2
- Proposed change no.3
- Proposed change no.4

Our response is:

☐ Approved

☑ Not approved 12/07/1999 10:46:56 AM

**Thanks for responding to this proposed change.**

Proposed change:

General proposal: Ref.: Our meeting with client on September 23, 1998:

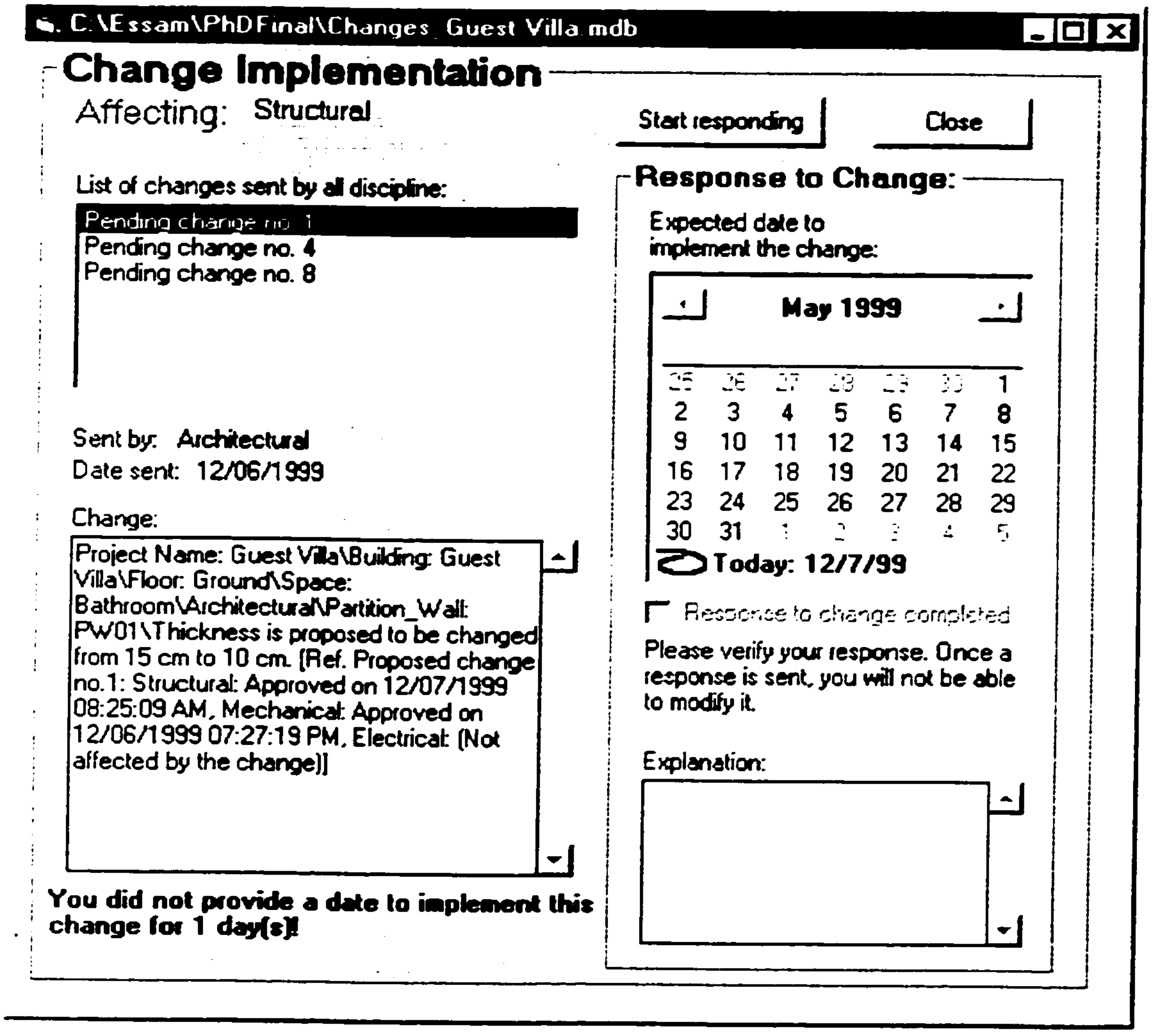
The client requested to remove the two columns at axes F-5 and F-7 in both the ground and first floors to provide clear spaces in the main entrance hall (ground floor) and in the recreation hall (first floor).

Approval explanation/Condition:

This is a major change.

**Fig. C4. Response to the Architect's General Change Proposal.**

## Appendix D: The "Structural" Engineer Receiving the Three Applied-Changes by the "Architect" for the Case Study in Chapter 6.



**Change Implementation**

Affecting: Structural

List of changes sent by all discipline:

- Pending change no. 1
- Pending change no. 4
- Pending change no. 8

Sent by: Architectural

Date sent: 12/06/1999

Change:

Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Partition_Wall: PW01\Thickness is proposed to be changed from 15 cm to 10 cm. [Ref. Proposed change no.1: Structural: Approved on 12/07/1999 08:25:09 AM, Mechanical: Approved on 12/06/1999 07:27:19 PM, Electrical: [Not affected by the change]]

**You did not provide a date to implement this change for 1 day(s)!**

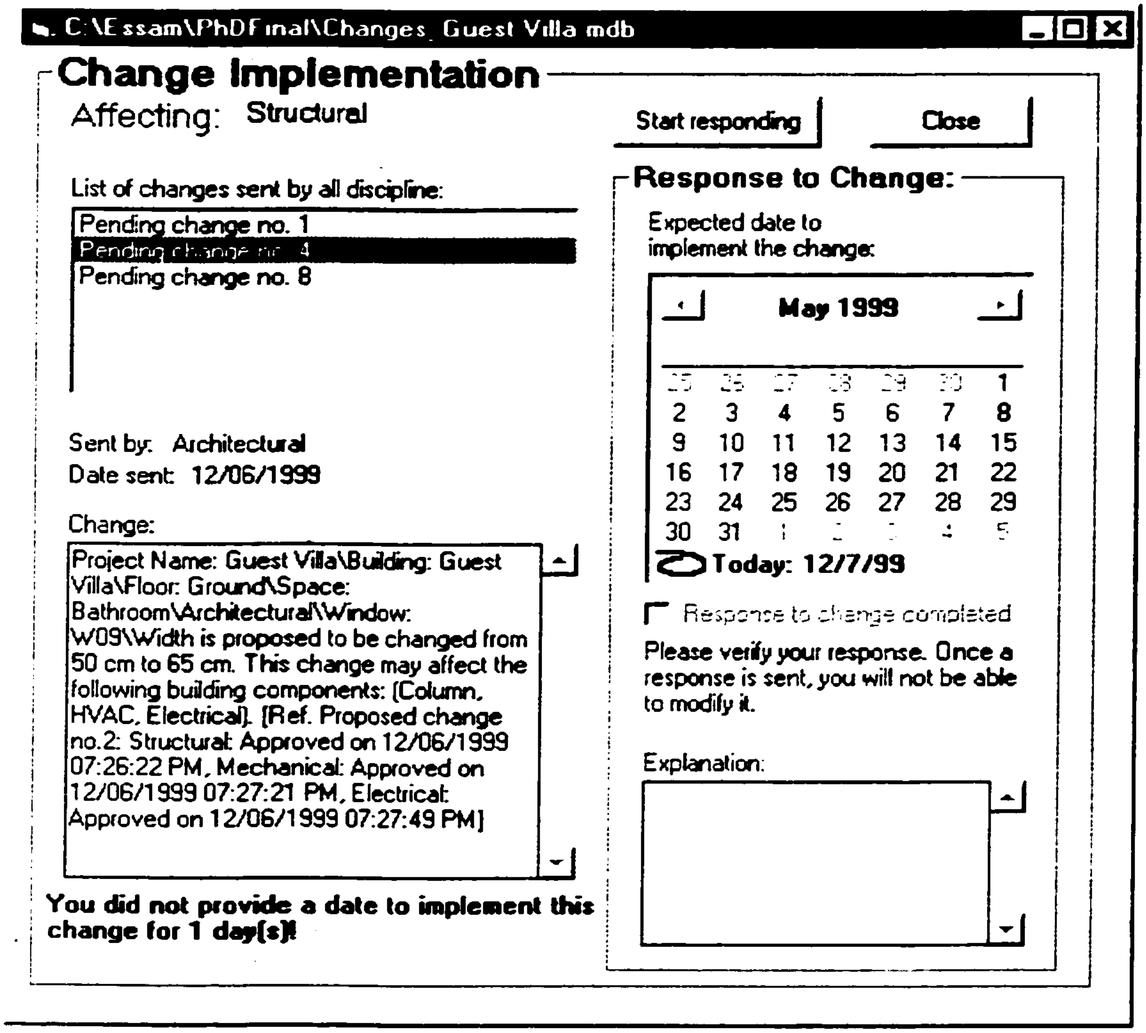
**Response to Change:**

Expected date to implement the change:

☐ Response to change completed

Please verify your response. Once a response is sent, you will not be able to modify it.

Fig. D1. Applied-Change Number 1 (Pending-Change Number 1).



**Change Implementation**

Affecting: Structural

List of changes sent by all discipline:

Pending change no. 1
Pending change no. 4
Pending change no. 8

Sent by: Architectural
Date sent: 12/06/1999

Change:

Project Name: Guest Villa\Building: Guest Villa\Floor: Ground\Space: Bathroom\Architectural\Window: W09\Width is proposed to be changed from 50 cm to 65 cm. This change may affect the following building components: [Column, HVAC, Electrical]. [Ref. Proposed change no.2: Structural: Approved on 12/06/1999 07:26:22 PM, Mechanical: Approved on 12/06/1999 07:27:21 PM, Electrical: Approved on 12/06/1999 07:27:49 PM]

**You did not provide a date to implement this change for 1 day(s)!**

**Response to Change:**

Expected date to implement the change:

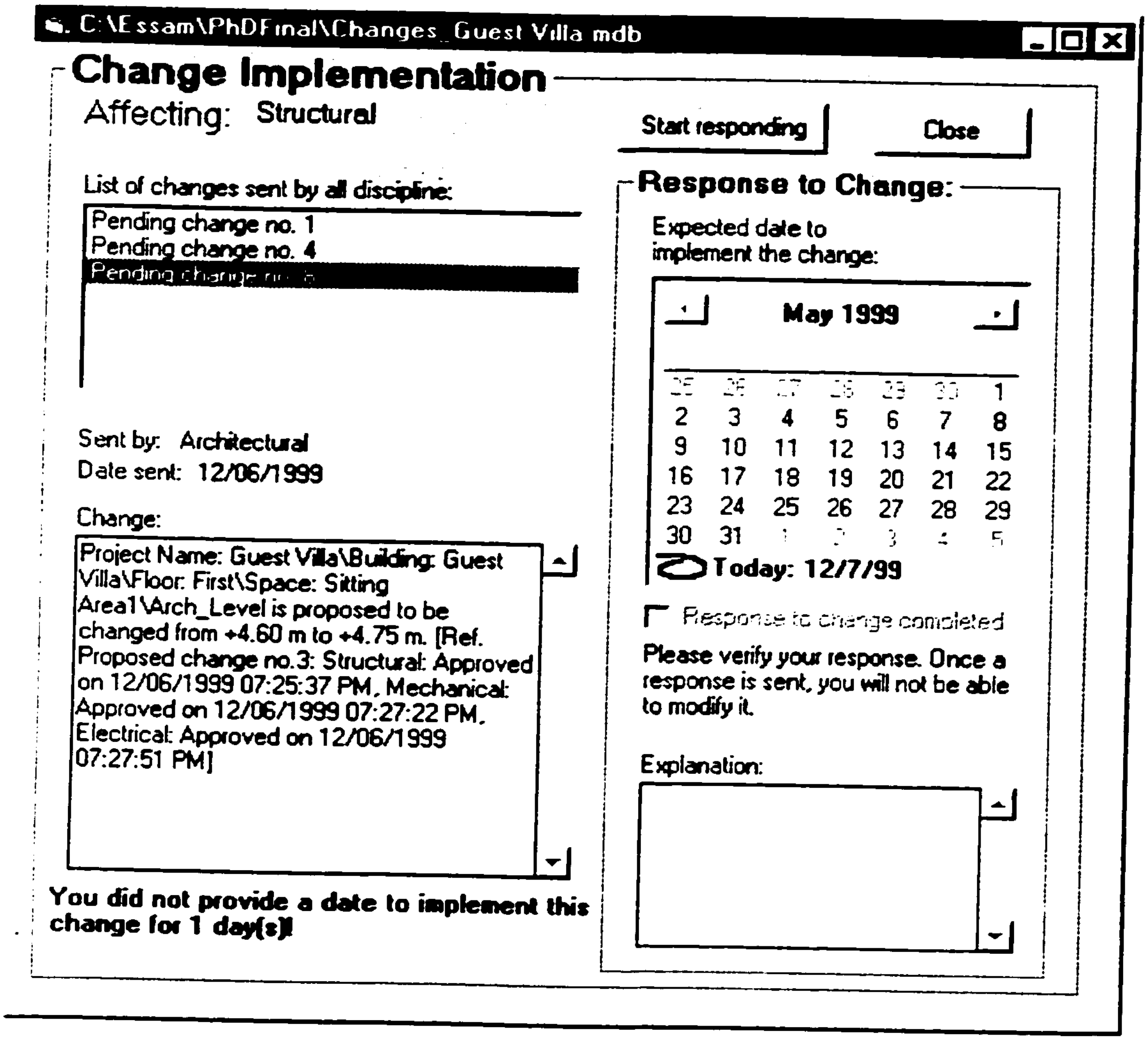
**Today: 12/7/99**

☐ Response to change completed

Please verify your response. Once a response is sent, you will not be able to modify it.

Explanation:

Fig. D2. Applied-Change Number 2 (Pending-Change Number 4).



**Change Implementation**

Affecting: Structural

List of changes sent by all discipline:

Pending change no. 1
Pending change no. 4
Pending change no. 8

Sent by: Architectural
Date sent: 12/06/1999

Change:

Project Name: Guest Villa\Building: Guest Villa\Floor: First\Space: Sitting Area1\Arch_Level is proposed to be changed from +4.60 m to +4.75 m. [Ref. Proposed change no.3: Structural: Approved on 12/06/1999 07:25:37 PM, Mechanical: Approved on 12/06/1999 07:27:22 PM, Electrical: Approved on 12/06/1999 07:27:51 PM]

**You did not provide a date to implement this change for 1 day(s)!**

**Response to Change:**

Expected date to implement the change:

| | | | | | | |
|---|---|---|---|---|---|---|
| 25 | 26 | 27 | 28 | 29 | 30 | 1 |
| 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| 30 | 31 | 1 | 2 | 3 | 4 | 5 |

☐ Response to change completed

Please verify your response. Once a response is sent, you will not be able to modify it.

Explanation:

Fig. D3. Applied Change Number 3 (Pending Change Number 8).

# Appendix E: The Questionnaire for Evaluating the Proposed System.

Name:________________________ (Optional) **Company/University:** ______________________________ (Optional)

I am: ☐ Student ☐ Faculty
☐ Other (Specify): ________________

**Background:** ☐ I have design experience in: ______________ (A/S/M/E)
☐ Other (please specify): ___________________________

Please answer the following using a score from 1 (Low/Bad) to 5 (High/Very Good).

| | **No.** | **Question** | **Score (1 to 5)** | **Comments/Suggestions** |
|---|---|---|---|---|
| **Overall System Features** | 1 | Usefulness of the library of building components | | |
| | 2 | Usefulness of storing project information in a tree | | |
| | 3 | Usefulness of access rights | | |
| | 4 | Usefulness for coordination among the members of a design team (one discipline) | | |
| | 5 | Usefulness for coordination among the multidisciplinary design teams | | |
| | 6 | Potential for time and effort savings | | |
| | 7 | Potential for solving communication problems | | |
| | 8 | Attractiveness to designers | | |
| | 9 | Usefulness if used on the web | | |
| | 10 | Changes to traditional work habits | | |
| | 11 | Attractiveness to small design firms | | |
| | 12 | Attractiveness to large design firms | | |
| | 13 | System security | | |
| | 14 | Overall efficiency | | |
| | 15 | Overall ease-of-use | | |
| **Representation of Design Elements** | 16 | Usefulness of storing/viewing drawings & specs. | | |
| | 17 | Usefulness of storing design rationale | | |
| | 18 | Effectiveness of representing design rationale as: desired performance/values/affected components | | |
| | 19 | Usefulness of storing default route of changes | | |
| | 20 | Adequacy of representing the components at space boundaries (e.g., doors, walls, beams, etc.) | | |
| | 21 | Usefulness of having components automatically send any changes made to their values | | |
| **Management of Changes** | 22 | Usefulness of getting approvals of other disciplines on change-proposals | | |
| | 23 | Usefulness of warning designers to implement changes sent to them by other disciplines (i.e., consider the implications of changes and respond) | | |
| | 24 | Usefulness of asking designers to provide expected dates of implementing changes | | |
| | 25 | Usefulness of the reporting system | | |
| | 26 | Usefulness of storing the history of all changes | | |

Other comments and/or **suggestions:** ______________________________________

Expected barriers to system **use:** ______________________________________

# Appendix F: The Evaluation Results of the Questionnaire.

| Section (1) | Question Number (2) | Number of respondents provided the score of: | | | | | Total score (8) | Total number of Respondents (9) | Average Score/question (10) | Average score/section (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 (3) | 2 (4) | 3 (5) | 4 (6) | 5 (7) | | | | |
| Overall System Features | 1 | --- | --- | 1 | 6 | 42 | 237 | 49 | 4.84 | **4.42** |
| | 2 | --- | 2 | 7 | 18 | 23 | 212 | 50 | 4.24 | |
| | 3 | --- | --- | --- | 8 | 42 | 242 | 50 | 4.84 | |
| | 4 | --- | 1 | 14 | 20 | 14 | 194 | 49 | 3.96 | |
| | 5 | --- | --- | 1 | 13 | 36 | 235 | 50 | 4.70 | |
| | 6 | --- | --- | 3 | 28 | 16 | 201 | 47 | 4.28 | |
| | 7 | --- | --- | 3 | 11 | 34 | 223 | 48 | 4.65 | |
| | 8 | --- | --- | 4 | 18 | 28 | 224 | 50 | 4.48 | |
| | 9 | --- | --- | 3 | 19 | 25 | 210 | 47 | 4.47 | |
| | 10 | --- | --- | 14 | 21 | 12 | 186 | 47 | 3.96 | |
| | 11 | --- | 2 | 23 | 16 | 5 | 162 | 46 | 3.52 | |
| | 12 | --- | --- | 1 | 17 | 27 | 206 | 45 | 4.58 | |
| | 13 | --- | --- | 1 | 9 | 40 | 239 | 50 | 4.78 | |
| | 14 | --- | --- | 2 | 18 | 25 | 203 | 45 | 4.51 | |
| | 15 | --- | --- | 1 | 23 | 25 | 220 | 49 | 4.49 | |
| Representation of Design Elements | 16 | --- | 1 | 5 | 22 | 21 | 210 | 49 | 4.29 | **4.57** |
| | 17 | --- | --- | --- | 14 | 34 | 226 | 48 | 4.71 | |
| | 18 | --- | --- | 3 | 28 | 15 | 196 | 46 | 4.26 | |
| | 19 | --- | --- | 1 | 7 | 39 | 226 | 47 | 4.81 | |
| | 20 | --- | --- | 1 | 25 | 21 | 208 | 47 | 4.43 | |
| | 21 | --- | --- | --- | 5 | 42 | 230 | 47 | 4.89 | |
| Management of Changes | 22 | --- | 1 | --- | 6 | 42 | 236 | 49 | 4.82 | **4.81** |
| | 23 | --- | --- | 1 | 1 | 47 | 242 | 49 | 4.94 | |
| | 24 | 1 | --- | 2 | 21 | 25 | 218 | 49 | 4.45 | |
| | 25 | --- | --- | --- | 3 | 42 | 222 | 45 | 4.94 | |
| | 26 | --- | --- | --- | 5 | 44 | 240 | 49 | 4.90 | |

**Average overall score = 4.53**

Notes:

1. Total attendants = 51.
2. Columns 3, 4, 5, 6, and 7 represent the number of respondents providing scores of 1, 2, 3, 4, and 5, respectively.
3. Column 8 represents the total score calculated for each question (e.g., the score of question 1 = 1*3 + 6*4 + 42*5).
4. Column 9 represents the total number responded to each question (e.g., 49 for question 1).
5. Column 10 represents the average score for each question (e.g., the average score for question 1 = 237/49)
6. Column 11represents the average score for each section (e.g., the average score for section 3 = 4.82+4.94+4.45+4.94+4.90/6).

# Appendix G: Average Scores for all Questions in the Questionnaire.