CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Case-Based Reasoning and Hypermedia: Enabling Technologies for Construction Experience Transfer

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SUMMARY

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1. Abstract:

Construction projects are vast repositories of knowledge and skills of various kinds. The highly dynamic nature of construction makes the knowledge and skills available on construction projects extremely transitory. The turnover and migration of workers, changes in phase and the lack of convenient access to stored experience-related information are major stumbling blocks in the transfer and effective utilization of construction experience.

This research focused on the issue of using prior experience from past projects as primary inputs to the process of carrying out problem-solving tasks in the design and execution phases of current and future projects. It identifies the major obstacles to experience transfer, develops a rationale for choosing knowledge-based decision-aiding systems rather than fully automated knowledge-based systems for use as mediums of experience transfer and develops a software architecture for the development of such knowledge-based systems.

The research also identified the domain of concrete mix design for the development and testing of an experience transfer system and established the point of departure for future research work in this area. The main focus of the prototype development effort will be to build and test a computer-based system which would design concrete mixes through the retrieval and adaptation of prior mix designs. This part of the research will be carried out as part of the author's doctoral dissertation work.

2. Subject:

• What is the report about in laymen's terms?

This report presents an attempt at developing an understanding of the principal issues involved in the transfer of construction experience from the perspective of problem-solving and using this understanding to configure a hybrid computer-based system which would facilitate the transfer of construction experience from past projects to current and future projects and its utilization for solving day-to-day problems on construction sites.

It also lays the foundation for the author's doctoral research work involving the development and testing of a computer-based system for the design of concrete mixes using the information contained in similar mix designs (stored in the computer) as the starting point.

- What are the key ideas or concepts investigated?
  - What is construction experience?
  - The need for experience transfer in construction
  - Motivation for a computer-based medium for transferring construction experience
  - What strategy will be most suitable for the development of the experience transfer medium - decision-aiding or total automation?
  - Rationale for the selection of the strategy
  - What factors affect the selection of technologies for the transfer and utilization of construction experience?
  - What role does the human user play in a computer-based experience transfer system?
  - Motivation for the use of case-based reasoning in construction experience transfer
  - Relevance of hypermedia to construction experience transfer
  - What are the advantages and disadvantages in using a computer-based experience transfer medium?

- What is the essential message?

  Hybrid computer-based systems using case-based reasoning and hypermedia technologies could provide the key to solving the experience transfer problem.

3. Objectives/Benefits:

- Why did CIFE fund this research?

  Out of recognition of the need to find a solution to the experience transfer problem in construction.

- What benefits does the research have to CIFE members?

  The research provides a foundation for future efforts involving the development and deployment of computer-based experience transfer systems.

- What is the motivation for pursuing the research?

  There is a long-felt need in the construction industry for the use modern computer technologies in the development of effective mediums for the transfer of construction experience from past projects to current and future projects and their utilization in day-to-day problem-solving on construction sites.

- What did the research attempt to prove/disprove or explore?

  The research attempted to explore the feasibility of the use of case-based reasoning and hypermedia technologies for developing experience transfer systems in construction.

4. Methodology:

- How was the research conducted?

  The first step involved a study of existing literature pertaining to experience transfer programs in the construction industry and prior research done in the area. This was followed by discussions with representatives of some of the leading firms in the construction industry. The next step involved an in-depth study of the case-based reasoning and hypermedia paradigms in relation to their applicability to construction experience transfer. The final step involved the development of a software configuration to develop and test a prototype experience transfer system.

- Did the investigation involve case studies, computer models, or some other method?

  The investigation involved the informal use of the case-study approach.

5. Results:

- What are the major findings of the investigation?

  (a) Case-based reasoning and hypermedia technologies could be utilized to develop computer-based problem-solving systems aimed at day-to-day problem-solving on construction projects.

  (b) Established the point of departure for future research work involving the development and testing of a computer-based problem-solving system in the concrete mix design domain.

- What outputs were generated (software, other reports, video, other)

  Engineer's thesis titled "Case-Based Reasoning and Hypermedia: Enabling Technologies for Construction Experience Transfer"

6. Research Status:

- What is the status of the research?

  First phase culminating in the development of a software configuration for a computer-based construction experience transfer system completed.

- What is the logical next step?

  Development and testing of a prototype computer-based experience transfer system in the domain of concrete mix design .

- Are the results ready to be applied or do they need further development?

  Further development is required.

- What additional efforts are required before this research could be applied?

  Prototype development and testing of a computer-based experience transfer system is required before results of this research can be applied in the field.

This report is a reprint of the author's Engineer thesis titled "Case-Based Reasoning and Hypermedia: Enabling Technologies for Construction Experience Transfer". The author's thesis advisor was Prof. Boyd C. Paulson

PREFACE

This thesis presents an attempt at developing an understanding of the principal issues involved in the transfer of construction experience from the perspective of problem-solving and using this understanding to configure a hybrid computer-based system which would facilitate the transfer of construction experience from past projects to current and future projects and its utilization for solving day-to-day problems on construction sites.

I thank Professor Boyd C. Paulson for his help, support and guidance during my graduate study at Stanford University. His counsel has been of great value to me on both academic and personal levels. In particular, I appreciate the time he spent in reading and correcting drafts during his trips abroad.

I am grateful to Professors Ray Levitt, Bob Tatum, Martin Fischer, Paul Teicholz and Victor Sanvido for their helpful suggestions and the Center for Integrated Facility Engineering, Stanford University for providing me with financial support to conduct this research.

Finally, I would like to thank my family and friends for their steadfast support, help and encouragement during the most difficult periods of my graduate study.

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INTRODUCTION

1.1. The Problem

A construction project brings together a wide variety of knowledge and skills under its ambit, all aimed at fulfilling the needs of the owner. Knowledge and skills could be collectively called "experience." This experience could vary from the commonplace to the extremely specialized, typically ranging from craft skills like carpentry, iron-work, painting and plumbing to managerial and administrative experience required to guide a project to its culmination safely and efficiently. Thus construction projects are a vast repository of experience (knowledge and skills) of various kinds.

Construction projects are, more often than not, unique. Unlike manufacturing, each project is designed and executed to serve a specific need of the owner. The nature of the work and the constitution of the work force in a construction project change with time.

The dynamic nature of construction projects makes the experience available on a project transitory. Not only is the experience lost or otherwise dispersed due to the migration of workers and staff to other projects, but as the project progresses towards completion it passes through phases which it will never enter again during its lifetime. Even if the project personnel have been conscientious enough to maintain records in the form of as-built drawings, still photographs and written descriptions, these would soon be lost or at best stored in locations which do not afford ready access to the stored information. Reams of paper stashed away in the basement of a building is a disincentive even for the most persevering project personnel desiring access to some previously recorded information, assuming in the first place that they can correctly locate the particular file in which this information is stored.

1.2. What is Construction Experience?

For the purposes of this thesis, construction experience is defined as that collection of knowledge and skills developed as a result of the planning, design and execution of one or more activities on a construction project. Such knowledge includes information pertaining to any project-related activity and artifacts involved in such activity, right from the time that an owner feels the need for a project until the time it ceases to be of any interest to the organization in question.

For knowledge to be transferred and used on future projects it has to be first recognized, captured and represented. Recognition involves determining the content and usefulness of the knowledge that is to be transferred. The content of the knowledge varies with the organization that wants the knowledge transferred. The capture of knowledge involves recording experience in one or more of text, graphics, video and audio formats.

This thesis discusses the *representation and use* of prior experience. The research did not concern itself with the *recognition and capture* of such experience. It is not a reflection of the relative importance of the three major issues involved in computer-based experience transfer (i.e., recognition, capture and representation), but rather is an attempt at defining the scope of the research. Recognition and capture are difficult facets of the experience transfer problem and are potential areas for future research.

1.3. Need for Experience Transfer in Construction

The loss of project-based experience is unfortunate, because some of this lost experience could have been adapted and put to use on other projects with similar site conditions. Worse still is the loss of experience and skills due to personnel turnover and migration. As far as the organization employing the workers is concerned, the experience is permanently lost. Another negative effect of personnel turnover is "experience dispersion," i.e., the experience is now no longer a cohesive whole. Employees may carry to other projects and organizations only part of the experience required for executing the work. In course of time even this experience fades away due to disuse.

The problem of experience transfer is more acute in the execution phase of construction projects than in the design phase. The study conducted by Reuss and Tatum [Reuss 93] has shown that although the increased utilization of sophisticated computer tools in design (e.g., CAD) offers some avenues for the inter-project transfer of *design* experience, construction industry professionals are frustrated by the absence of suitable tools for the transfer of *construction* experience between projects. To transfer experience between projects, managers transfer people.

According to Reuss and Tatum:

> "Transferring construction experience between projects can make significant contributions to achieving the project objectives of cost, schedule, quality and safety. The knowledge gained allows construction teams to repeat the successful techniques and avoid the mistakes of previous projects. Without transferring experience, the construction industry does not "learn" and improve as it should."
>
> [Reuss 93, p. 5]

Quite often project personnel assigned to a particular project find that they lack the experience to solve problems that have cropped up on site. Such problems could vary in a broad spectrum from those related to execution of field tasks like a site dewatering problem to managerial problems like legal and contractual problems caused by delay. In such cases a commonly used method of experience transfer is the use of an experienced project manager, project engineer or project superintendent who is temporarily assigned by top management to another project site to help solve a problem or get the project back on track. These individuals are much sought after for the wealth of experience they possess. Transferring knowledge through such a process is expensive, causes disruption of work and often leads to loss of morale in project personnel already beset with the kinds of problems that top management has perceived to be beyond their problem-solving capabilities. In addition to the selection of the problem-solving method, the decision-maker must also evaluate the current situation to take into account the impact the problem and the solution have on the physical, social, psychological, economic, contractual, legal, and temporal environments. A thorough evaluation is rarely performed on construction projects due to the pressures of "getting the job done" and at best is incomplete.

Thus there is a compelling need to develop an effective experience transfer mechanism in the construction industry.

1.4. Purpose, Scope and Research Objectives

1.4.1. Purpose

To be effectively put to use on future projects, experience has to be captured and stored in a form which facilitates its efficient retrieval and affords easy understanding and utilization by the end-user.

The main purpose of this research was to lay the foundation for the development and testing of a methodology that could be utilized to develop and test a computer-based experience transfer system for transferring construction experience from past projects and utilizing such transferred experience for carrying out day-to-day problem-solving tasks on construction projects. The research will build the foundation for future work in the area involving the development and testing of a knowledge-based decision-aiding system in a test domain.

1.4.2. Scope

This research focuses on the issue of using prior experience from past projects as primary inputs to the process of carrying out problem-solving tasks in the design and execution phases of current and future construction projects. It identifies the major obstacles to experience transfer and develops a rationale for choosing knowledge-based decision-aiding systems rather than fully automated knowledge-based systems for use as mediums of experience transfer. A conceptual system architecture for the development of such knowledge-based decision-aiding systems will be discussed.

The technologies considered are case-based reasoning (CBR) and hypermedia. The underlying basis for the selection of each of these technologies is discussed. A domain for implementing a decision-aiding system using techniques borrowed from CBR was selected and the motivations for the development of a case-based decision-aiding system in this domain will be presented.

The thesis will also present the results of a literature survey and establish the point of departure for future research involving the development and testing of a case-based decision-aiding system in the field of concrete mix design.

1.4.3. Specific Research Objectives

The specific research objectives were:

1. Development of a rationale for the use of case-based reasoning and hypermedia technologies in the development of intelligent computer-based decision-aiding systems which would serve as mediums for the transfer and utilization of construction experience from past projects to current and future projects.
2. Selection of a domain for implementing a computer-based decision-aiding system which would serve as a medium of experience transfer.
3. Presentation of a rationale for the development of a knowledge-based system in the selected domain using the principles of case-based reasoning.
4. Establishing the point of departure for future research involving the development of a proof-of-concept prototype.

1.5. Reader's Guide

The main body of this thesis is organized as follows:

Chapter 2 first explains the need for a computer-based experience transfer system. This is followed by a detailed discussion of the significant issues that influence the configuration of the system. A high-level, conceptual configuration of a computer-based experience transfer system is presented at the end of the chapter.

The first section of Chapter 3 briefly discusses the principal concepts underlying case-based reasoning. The second section of this chapter explains major categories of case-based reasoning systems that have been developed thus far. The motivation for the use of case-based reasoning systems in the transfer and use of construction experience is presented in the third section. The final section of Chapter 3 discusses roles played by the human user and the case-based system in problem-solving in construction.

Chapter 4 begins with an overview of hypertext and hypermedia followed by a presentation of the basic structure of hypertext. A detailed discussion of the relevance of hypermedia to the issue of transfer of construction experience is presented in the final section of this chapter.

Chapter 5 first talks about the predominant methods of information retrieval in hypertext, drawbacks with these methods, and the techniques employed to mitigate the effects of the drawbacks. It lays the foundation for the development of a rationale in the second section for the use of CBR in conjunction with hypertext for information retrieval. This is followed by a discussion of the conceptual configuration of a hybrid decision-aiding system which can function as an experience transfer medium. The fourth section of this chapter explains the software architecture of the hybrid system. The last section lists the major advantages and disadvantages of the system.

Chapter 6 deals with the use of the case-based reasoning paradigm in the design of concrete mixes. The first section presents the reasons for the selection of the case-based reasoning component for testing the experience transfer system. Section 2 of the chapter discusses the motivation for the use of artificial intelligence in the design of concrete mixes. Section 3 explains the purpose, scope and objectives of the development of a computer-based system for the design of concrete mixes using prior mix designs followed by a presentation of the theoretical underpinnings of concrete mix design in section 4. Section 5 establishes the point of departure of the current work which uses case-based reasoning to design concrete mixes from contemporary mix design methods. The final section discusses the impact of case-based design on the field of concrete technology.

Chapter 7 discusses the conclusions that could be drawn from this research, summarizes the contributions, and offers some suggestions for future work.

2

THE EXPERIENCE TRANSFER MEDIUM

2.1. Motivation for a Computer-Based Experience Transfer Medium

We are in an era where the world is moving rapidly from an industrial society to a post-industrial society, where information exchange plays a pivotal role in its development and sustenance. Earl describes our post-industrial society as an information society where the key resource is knowledge and where information technology is the enabling mechanism [Earl 89]. Hodge explains the importance of information and the role played by systems that transmit information as follows:

> " Data transmission systems are the transforming resource of the information society, just as in the industrial society, where created energy — electricity, oil, nuclear power — is the converting element. . . . The strategic resource of the information society is theoretical knowledge, just as the strategic resource of an industrial society is capital and the strategic resource of the preindustrial society was raw materials. Instead of a society based on the labor theory of value such as that propounded by Adam Smith or Karl Marx, the information society rests on a knowledge theory of value. Value is increased not by labor but by knowledge. In contrast with the industries of an industrial society, the industries representative of the last quarter of the 20th century are science-based industries. They are derived fundamentally from the application of the findings of theoretical knowledge. This has been an impetus for the rapid development and use of the computer and information systems."
>
> [Hodge 84, p. 14]

The ideas expressed in the previous paragraphs apply to business management in general, but they are very much relevant to the construction industry as well. Betts et al [Betts 91] have suggested that organizations involved in construction will ultimately have to think strategically about their use of information technology; i.e., they will have to find ways of harnessing the power of information technologies to achieve the organizational objectives set by top management. According to the same authors, plans for such new uses of information technology in construction, which look beyond merely using this technology for improving the efficiency of discrete operations, are being made by individual organizations in the construction industry. The concept of the strategic use of modern information technology at the organizational level could also be translated into the strategic use of this technology at the project level. One such use is the capture of prior experience from past projects followed by its transfer and utilization in current and future projects. As mentioned in Chapter 1, this thesis deals with the transfer and utilization of construction experience, not its physical capture.

The effective transfer and utilization of experiential knowledge hinges on the presence of a medium which would facilitate the efficient storage and retrieval of such knowledge. Current mediums for experience transfer in the industry are paper documents, photographs and formal and informal discussions. Although one cannot deny the usefulness of paper documents, photographs and formal and informal discussions in certain short-term situations like briefing a crew by the foreman prior to the execution of a task or in weekly co-ordination meetings on site, they are inefficient as permanent, long-term methods of experience transfer. Discussions and oral instructions are useful for initiating prompt action but more often than not such information is not retained within the organization due to worker turnover or simply due to the fading of such knowledge from a person's memory. Although paper documents and photographs provide more permanent methods of experience transfer than discussions and oral instructions, they often suffer from lack of quick and convenient access. Discussions conducted with members of Bechtel Corporation's Construction Technologies Research and Development Group at their corporate head office in San Francisco revealed that about forty percent of an engineer's time is spent in searching for relevant information. Most of this time is spent in tracking down the physical location of printed documents and searching through unrelated or irrelevant information. This results in wastage of costly engineer time and lower quality of work as it is based on what was found, and not on the current information available. Recent work in the construction industry [Reuss 93] and in academia [Tatum 93, Kartam 94] in the area of experience transfer bears testimony to the fact that there is a growing consensus that a computer-based system is the answer to the experience transfer problem. As a more general motivation for the use of computer-based systems for the storage and retrieval of information in construction, Paterson argues that:

> "Human beings, as data handling machines, are particularly good at handling very large quantities of data in a very imprecise way, but poor at repetitive and precise retrievals. Variety, for the sake of variety, is sometimes introduced in order to break the monotony of routine jobs. These deficiencies are a considerable handicap in a society which demands ever-increasing precision in all processes. Because the manual handling and filing of routine data is considered to be below the level of importance to management, it is often delegated to comparatively junior members of the staff, who, quite reasonably, often organize the system for the ease of putting the information away, rather than for the real purpose, which is the easy retrieval of the information at a later date."
>
> [Paterson 77, p. 27]

2.2. Conceptual Framework for the Experience Transfer Medium — Relevant Issues

2.2.1. Total Automation vs. Decision Aiding

This thesis looks at the issue of transfer of construction experience from the perspective of its utilization for problem-solving on construction projects. In developing a strategy to solve such problems, the problem-solver has to draw upon and process a wide spectrum of complex pieces of inter-related information from the external world and link it with his or her own intuition, judgment, common sense and technical knowledge. Therefore, the question that has to be addressed in the context of the development of a computer-based medium of experience transfer is whether it is feasible to develop and deploy in such unstructured domains as construction, fully automated systems that could be entrusted with the task of decision-making without the benefit of human supervision.

A study of expert system technology in support of image analysts combing through imagery produced by Digital Synthetic Aperture Radar systems revealed that such technology was inappropriate due to the following domain characteristics: the problem is not recurrent for the foreseeable future and an expert is not available to help populate the knowledge base [Elofson 92]. In fact, a study of the applicability of expert systems will show that in the ideal case the essential requirements for the successful development and utilization of fully automated decision support systems using expert system technology are:

(a) small and well-bounded domains

(b) recurrent nature of problems

(c) availability of comprehensive knowledge of problem situation characteristics

(d) availability of an expert who could provide generalizations of the problem-solving process he or she would have adopted when faced with the same problem.

However, what we obtain on a typical construction project in relation to the development of expert systems are:

(a) We would like to have the domain as large as possible.

(b) The problem may not be recurrent or may be recurrent at extremely low frequencies.

(c) Not all the characteristics of the problem situation are known; an expert who could provide generalizations of the problem-solving process is usually not available.

(d) Often an exhaustive determination of the kinds of problems that could occur is not possible.

(e) Incomplete knowledge of the factors impacting the problem situation makes finding optimal solutions an unrealistic goal.

Thus it stands to reason that in the highly complex and dynamic environment of the typical construction project, a viable strategy for developing computer-based systems for problem solving would be one of decision-aiding rather than full automation.

2.2.2. Factors Affecting the Selection of Technologies for the Transfer and Utilization of Construction Experience

Within the scope of this thesis, the two important factors that have to be taken into consideration in the selection of appropriate technologies for the transfer and utilization of construction experience for use in the day-to-day activities on construction projects are:

(a) retrieval of information relevant to the situation at hand, and

(b) ease with which the retrieved information can be understood by the end-user.

Information retrieval, as it is commonly used, refers to activities involved in searching a body of information in order to find items that deal with a specific topic of interest [Lancaster 78]. Within the scope of this thesis, information retrieval is the process of directly interrogating the computer-based system to resolve specific requests for information required to assist project personnel in the execution of day-to-day activities on a construction site. Hartley et al characterize information retrieval as an interactive search process:

> "The search process is dynamic and interactive: results are made available almost immediately to the searcher who can then, according to the usefulness or otherwise of the information retrieved, refine the original request and continue the interaction until the best result possible is obtained. Some searches may only take a few minutes: others may last half an hour or more."
>
> [Hartley 90, p. 1]

In the development of intelligent systems, the two most popular retrieval-oriented technologies that have emerged over the past several years are Case-Based Reasoning (CBR) and Information Retrieval (IR) [Barletta 93]. CBR systems solve problems by retrieving similar cases (episodes of problem situations) and adapting these cases to suit the requirement of the current problem situation. However, with regard to IR systems Barletta states that they:

> ". . . retrieve relevant documents (texts) from large text databases. . . . the user just types in a free-form description of a particular subject, and the system does the rest. Unlike querying a relational database, the user need not specify precise matching parameters, just the problem description. . . . While CBR and IR systems can sometimes find exact matches between a query and retrieved information, their

> real power is in finding relevant, inexact matches when an exact match cannot be found. This is also a fundamental distinction between CBR and IR systems on one hand, and SQL querying of relational databases on the other. While it is possible to find "inexact" matches in a relational database by specifying a complex SQL statement with the appropriate ranges and disjunctive conditions, these statements can be hard to build, even if you know what you want to look for."
>
> [Barletta 93, p. 2]

However, IR systems have the following disadvantages:

(a) They focus almost exclusively on narrative text and there are many sources of problem-solving data that have no free-form text or mixed representations with limited text.

(b) IR systems are principally information storage and retrieval systems. They do not make assumptions about a user's problem-solving task. The main aim in such systems is to provide a generic indexing scheme that can be used regardless of the user's problem-solving context. However, the resulting lack of context-specificity limits the level of accuracy of retrieval that can be achieved [Barletta 93].

CBR systems, on the other hand, do not experience these disadvantages because they are based on the assumption that case information is generally available in mixed representational formats. As a consequence of this assumption, CBR systems support the use of (limited) free-form text, numbers, dates, lists, and symbolic feature types for indexing cases [Barletta 93]. Furthermore, CBR systems rely on knowledge of the problem-solving task to build context-specific case indices. This achieves high levels of accuracy of retrievals in these systems [Barletta 93]. Unfortunately, CBR systems in general cannot handle very large case libraries in the way that IR systems can.

From the perspective of the transfer of construction experience, any medium which is required to serve as the vehicle for such transfer should, in the ideal case, possess both the accurate retrieval capabilities of a CBR system and the large information-handling capabilities of an IR system.

2.2.3. Role Played by the Human User

Given a problem, the knowledge required to solve the problem can be said to consist of one or more of the following types: relationships, analogies, hunches, rules of thumb, guesses, facts and experience. While computer-based systems perform as well as or sometimes even excel humans at the more routine and repetitive tasks, they are often found wanting in those problem-solving tasks that demand a high degree of creativity, common sense or intuition.

According to Alty:

> "In trying to automate the process, it is unlikely that we will remain completely successful. Usually a part of the solution process remains with the human being—often the difficult, judgmental parts of the process. This gives rise in any attempt at automation to the automation boundary (or human-computer interface). The position of this boundary will depend on the nature of the problem. In some cases—say salary-slip production—automation will be almost complete. In other cases—say personnel selection—the human part may still be quite large. However, as traditional computing techniques have improved, the boundary has moved inexorably reducing the human part."
>
> [Alty 89, pp. 124-125]

Viewed from the perspective of complexity, problem-solving knowledge could be classified into three categories:

(a) Straightforward knowledge

(b) Expertise

(c) Common sense

Alty defines these three categories of knowledge as follows:

> "Straightforward knowledge covers knowledge such as facts and relationships which can be relatively easily represented in traditional programs. Expertise is that peculiar type of knowledge that we generally ascribe to experts in a particular field . . .. Commonsense knowledge . . . (has) the greatest complexity and this might, at first sight, seem rather odd. Yet common sense is rather special and might be described as the expertise of the living. It is extremely wide ranging, utilizing a vast knowledge base of experience."
>
> [Alty 89, p. 125]

Figure 2.1 shows the location of the automation boundary and the progression of the boundary over the years as computing techniques have become more extensively used.

It is clear from the above discussion that in such unstructured domains as construction, problem-solving could involve the use of intuitive and commonsense types of knowledge which cannot at present be captured and represented in a form that could be manipulated by a computer. According to Kolodner:

> "Much of AI is sold to the world as fully automated expert systems, that is, systems based on rules that, given a problem statement, will produce a solution. Such systems have been highly successful in solving problems in many well-circumscribed domains. They have not been successful, however, in solving problems requiring creativity, broad commonsense knowledge, or aesthetic judgment."

[Kolodner 91, p. 52]

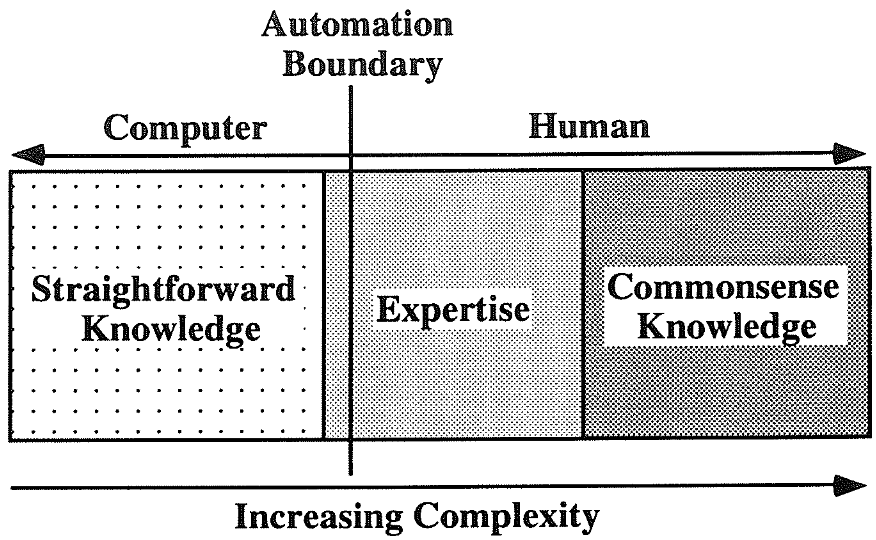

Figure 2.1. Categories of problem-solving knowledge ordered by level of complexity and the location of the automation boundary. (Adapted from Alty 89)

The question that has to be addressed at this stage is that given the current state of development of computer technology, is it possible to develop computer-based systems that can perform better than existing ones especially in areas that require common sense or intuitive knowledge? Kolodner claims that the answer to this question is "yes, if we can develop an appropriate symbiotic relationship between people and machines." [Kolodner 91, p. 53]

The approach suggested by Kolodner to develop such a symbiotic relationship is to examine the way people reason while solving problems, develop a cognitive model of this reasoning, and explore which parts of the process are easily done by people and which are found to be difficult [Kolodner 91]. We have to also examine whether those aspects of problem-solving found difficult by humans could be better performed by computers.

Researchers in the field of psychology have observed that people tend to reason from past experiences to solve problems. They reason from their own experiences if such experiences are relevant to the situation at hand or reason based on the experiences of others to the extent that such experiences are available to them [Riesbeck 89]. This kind of reasoning is called case-based reasoning.

> "Psychologists have observed, however, that people have several problems in doing analogical or case-based reasoning. Although they are good at using analogs to solve new problems, they are not always good at remembering the right ones. . . . However, computers are good at remembering. The idea in case-based decision-aiding is that the computer augments the person's memory by providing cases (analogs) for a person to use in solving a problem. The person does the actual decision making using these cases as guidelines. In

essence, computer augmentation of a person's memory allows this person to make better case-based decisions because it makes more cases (and perhaps better ones) available without the machine. At the same time, the person is free to use a reasoning method that comes naturally to make these decisions."

[Kolodner 91, p. 53]

If we examine problem-solving on construction sites, whether it is a site dewatering problem or a managerial problem caused by delay, one of the most common methods employed to solve problems is case-based reasoning, i.e., project personnel try to recall similar situations encountered by them in the past or consult colleagues who might have come across similar problems and use the retrieved information to solve the current problem.

In developing case-based decision-aiding systems for problem-solving on construction projects, the aim is to push the automation boundary in Figure 2.1 as far to the right as possible. Furthermore, since (a) reasoning from analogs or cases is a natural process for people, especially when there is much uncertainty or many unknowns, and (b) remembering the right cases is difficult, the idea of combining the reasoning abilities of a human user with the powerful storage and retrieval capabilities of the computer has merit.

"Because people have trouble remembering appropriate cases, the [computer-based] system will augment their memories by providing, at appropriate times, the relevant experiences of others. However, because people are better at dealing with aesthetics, ethics, creative adaptation, and judgment, we leave the real decision-making to people. That is, the computer will provide cases to human problem solvers at appropriate times to help them with such tasks as coming up with solutions, critiquing and evaluating solutions, and warning of potential problems."

[Kolodner 91, p. 57]

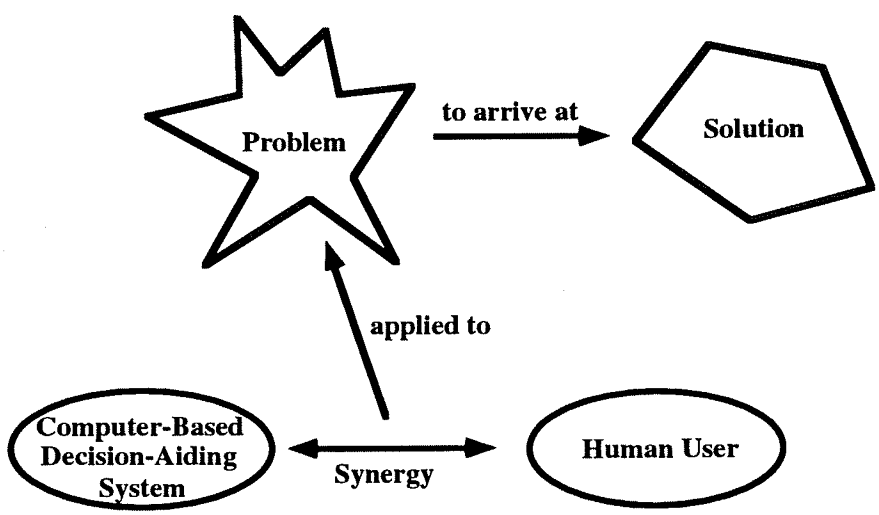

Figure 2.2. Conceptual configuration of computer-based problem-solving system.

Figure 2.2 shows a conceptual configuration of a problem-solving system where the synergy developed as a result of the interaction of a human user with a computer-based decision-aiding system is applied to problem-solving on construction sites.

This chapter presented the motivation for the development of a computer-based system to facilitate the transfer of construction experience from past projects to current and future projects. This was followed by a discussion of the relevant issues that affect the development of such a system and the component technologies that would be used. The discussion culminated in the presentation of a conceptual configuration for the system.

The next two chapters will present detailed discussions of the two technologies that would be used to build the system — case-based reasoning and hypermedia — as a prelude to the development of a software system architecture for an experience transfer system that utilizes these technologies.

3

CASE-BASED REASONING

3.1. What is Case-Based Reasoning?

While on a routine inspection of a construction site, an engineer noticed that the columns supporting the trestle beams of an overpass had particularly heavy reinforcement. He recalled that on an earlier project he had encountered a situation where a heavily reinforced concrete column supported two heavily reinforced continuous beams which intersected at the column. The specifications required the top (negative) reinforcement in the beams to be taken across the column junction into the adjacent beam for one-third of the span. He recalled encountering considerable difficulty in getting the top (negative) reinforcement in place due to the density of the reinforcement. Three such column junctions were cast using plasticizers in the concrete. On stripping forms it was found that there was heavy honey combing and each of the three column junctions had gaping holes where the concrete had not entered. The A/E blamed the contractor for poor workmanship and the contractor in turn blamed the A/E for poor detailing. Three beams had to be completely dismantled, the weak concrete around the column junction chipped and removed, and recast after placing additional bottom reinforcement in the beams adjacent to the ones dismantled. In addition, five needle vibrators had to be replaced. The cause of the problem was the lapping of top reinforcement at the junction. The high density of reinforcement also prevented concrete from being properly placed and consolidated, resulting in voids in the concrete at the junction. Due to ego conflicts and the intransigence of the parties involved, rework was started after a lengthy exchange of notices, filing of extra claims and heated arguments. It required the intervention of top management of both sides to settle the issue, by which time the activity became critical and further delay in completion of the rework caused two weeks delay in project completion. Needless to say, on the bridge project, by anticipating the problem well in advance of the actual work, the engineer was able to prevent the congestion of reinforcement by avoiding laps at the column junction.

In the example cited above, the engineer is recalling and using his experiences on a previous project in a similar situation to ward off a potentially problematic situation on the current project. The same experience could also be used in solving a problem — that of rectifying the defect of a structurally weak beam caused by severe honeycombing. In both these instances the engineer is using *case-based reasoning*. The process of retrieving the most relevant case from long-term memory is called *case-retrieval.*

> "We have so many cases available to us that finding them can be very tricky indeed. Human memory depends upon good methods of labeling cases so that they can be retrieved when needed."
>
> [Riesbeck 89, p. 7]

Recalling old experiences is called the *indexing problem* in case-based reasoning. It means finding the experience closest to the new situation in memory and is achieved in (computer-based CBR systems) by assigning indexes to experiences stored in memory so that they can be recalled under appropriate circumstances [Kolodner 93].

In the above example, if the affected beam on the current project is simply supported, then in order to solve the problem, the engineer would have to do everything that was done on the continuous beam on the previous project, but more importantly, would have to make appropriate adjustments to his solution on account of the beam being simply supported instead of continuous. In the present case, additional bottom reinforcement in the beams adjacent to the dismantled beams may not be required. This process of adjusting the solution to suit current requirements is known as *case-adaptation.* It could also be stated as the process of appropriately modifying an old solution to meet the demands of the new situation [Kolodner 93].

> "The basic idea in case-based reasoning is very simple:
>
> A case-based reasoner solves new problems by adapting solutions that were used to solve old problems."
>
> [Riesbeck 89, p. 25]

Researchers in the field of case-based reasoning claim that people almost always reason from cases if such cases are available to them. According to Riesbeck and Schank:

> " . . . the question here is not whether reasoning from prior cases is what you ought to do. The question is whether it is what people do do. Virtually, whenever there is a prior case available to reason from, people will find it and use it as a model for their future decision-making. This process of "case-based reasoning" can be very advantageous to a decision maker who knows a large number of cases and has been able to index them so that the most relevant cases come to mind when needed. . . . Case-based reasoning is the essence of how human reasoning works. People reason from experience. They use their own experiences if they have a relevant one, or they make use of the experience of others to the extent that they can obtain information about such experiences."
>
> [Riesbeck 89, p. 6]

Kolodner suggests that if we watch the way people around us solve problems, we are likely to observe case-based reasoning in constant use [Kolodner 91]. Attorneys, mediators and even day-to-day commonsense reasoning employ case-based reasoning. Other professionals like doctors and engineers are not taught to use case-based reasoning but often find that it provides a way to solve problems efficiently [Kolodner 93].

"In general, a second time solving some problem or doing some task is easier than the first because we remember and repeat the previous solution. We are more competent the second time because we remember our mistakes and go out of our way to avoid them."

[Kolodner 91]

3.2. Major Categories of CBR Systems

From the perspective of this thesis, case-based reasoning systems could be classified into two main categories:

(a) Automated case-based reasoners

(b) Retrieval-only aiding and advisory systems

Automated case-based reasoners are systems that do what is necessary to solve a problem and produce a solution. The only role of the human user in most such systems is to produce feedback to let the system know how the suggested solution had performed in the real world [Kolodner 93]. Examples of such systems are: CHEF, JUDGE, and CASEY.

CHEF is a case-based reasoning system developed in the area of Szechwan cooking [Hammond 89]. CHEF takes as input "goals that recipes can achieve (e.g., include fish, use stir-frying method, achieve savory taste); (and produces as output) a recipe that can achieve those goals" [Kolodner 93, p. 34]. CHEF is fundamentally a case-based planner and recipes are viewed as plans. CHEF uses the retrieve-and-adapt approach for creating its recipes by retrieving prior recipes that were successful under similar circumstances and modifying them to suit the current situation. The first step in creating a plan is to retrieve an old recipe that fulfills as many of its new goals as possible. CHEF indexes its plans by the goals they achieve.

JUDGE is a case-based reasoner that works in the domain of criminal sentencing. and "models a judge who is determining sentences for people convicted of crimes. The input is a description of the case, including the charge, the events that occurred, and the legal statutes regarding crimes of this nature, e.g., the range of imprisonment allowed and parole conditions" [Riesbeck 89, pp. 27 - 28]. JUDGE has in its case-base details of previous crimes and the sentences determined for each. The retrieved case is adapted to the current crime by adjusting the sentence based on the severity of the crime.

CASEY is a case-based diagnosis program in the domain of heart-failures [Kolodner 93]. The program "takes a description of a patient's symptoms and produces a causal network of possible internal states that could lead to those symptoms [Riesbeck 89, p. 30]. CASEY is built on top of a more complete model-based diagnostic program (Heart Failure Program) of "unprecedented accuracy" [Kolodner 93]. When a new case comes in, it looks for cases of similar, but not necessarily identical symptoms. If a good match is found, CASEY proceeds with adaptation taking into account differences in symptoms between old and new cases. If a sufficiently close match is not found, CASEY passes the case onto the Heart Failure Program, which performs the diagnosis and returns its results to CASEY to use another time [Kolodner 93].

In contrast to fully automated case-based reasoners, retrieval only or advisory CBR systems leave the critical decision-making process to the human user. Such systems merely retrieve the cases that are most relevant to the current situation and present them to the user. In suggesting both a context and a rationale for retrieval-only decision-aiding systems, Kolodner states that:

> ". . . creation of autonomous systems is only one way case-based reasoning can be used for system building. The most powerful thing about case-based reasoning, perhaps, is its fit with what people do. . . . . . people use case-based reasoning naturally in much of their everyday reasoning. In complex domains or those where a person is a novice, however, people do not always remember the most appropriate cases, sometimes because of bias, sometimes because they haven't yet encountered the appropriate experiences. Many people in the case-based reasoning community believe that case-based reasoning's biggest potential is in building interactive systems that can help people solve problems or teach them new domains.
>
> The emphasis in building interactive case-based systems has been on building interactive aiding and advisory systems. Just as there are several possible roles a human advisor can play in helping us solve problems, so too are there several possible roles a case-based advisory system can potentially play. It can act merely as a browsing facility, it can provide information in response to queries, it can act as a coach, looking over the shoulders of the human and providing guidance and suggestions, or it can act as a colleague, playing a role equal but complementary to that of the human user. Those systems that have been built to date have been browsing facilities and information providers."
>
> [Kolodner 93, p. 60]

Examples of such case-based aiding systems are: BATTLE PLANNER, CLAVIER and ARCHIE-2.

BATTLE PLANNER [Goodman 89] was one the first case-based advisory systems built. It plays the role of a coach for a novice in the domain of military battle planning. The user describes a battle situation to the system and tells the system his or her best guess at a solution. The system then retrieves cases that can be used to critique the solution. BATTLE PLANNER also extracts useful summary information from the cases it retrieves. The user utilizes the cases and summary information to critique his or her solution and propose a revised solution with the required modifications if the original solution is found to be inadequate. The user goes through successive iterations of this process until the cases that are retrieved give no more clues about generating a better solution.

CLAVIER [Barletta 89] is a system for configuring the layout of composite airplane parts in an autoclave. Autoclave loading is a black art and a causal model of what kinds of layouts work for specific sets of parts to be cured does not exist. The input to the system is a set of parts that requires curing. The output of the system is a design of layouts of the autoclave that will cure all the parts, getting as many of them cured on time as possible. CLAVIER was originally developed as an automated system but has been put into production as an advisory system [Kolodner 93].

ARCHIE-2 is a case-based aid for architects that is basically a story-based hypermedia browsing system in support of architectural design [Domeshek 93]. The user specifies his or her interests to the system which retrieves relevant documentation, stories, and guidelines for perusal. Stories and guidelines are organized graphically around design plans to allow easy transition between stories that are about the same building. They can also access multiple stories that illustrate the same guideline. Users can also request stories that are related in topic to one they are looking at [Kolodner 93].

3.3. Motivation for Use of Case-Based Reasoning in Construction Experience Transfer

Case-based reasoning has been proposed as a more plausible model of expert reasoning than rule-based expert systems [Slade 91, Kolodner 93, Riesbeck 89]. Early AI programs like DENDRAL [Buchanan 69] and MYCIN [Shortliffe 76] demonstrated that the problem-solving abilities of human experts could be simulated using rules. Production rule-based systems have been highly successful in vary narrow domains, but as experience with the development and use of such systems increased, so did the recognition of the drawbacks of such systems [Slade 91, Kolodner 91]. According to Slade, the main drawbacks with rule-based expert systems are as follows:

> "The first problem was knowledge acquisition. To build an expert system, a computer programmer (or knowledge engineer) had to sit with the human expert to determine what rules were appropriate for the given domain. The knowledge was difficult to uncover. . . . Often the informant articulated a set of rules that in fact did not accurately reflect his(her) own problem-solving behavior. For these reasons, this difficult knowledge-acquisition process became known as a bottleneck in constructing rule-based expert systems [Hayes-Roth 83].
>
> Second, the rule-based expert systems did not have a memory. . . For example, if a medical diagnosis program were presented with a patient with a certain set of symptoms, the program might have fired dozens or hundreds or thousands of rules to come up with a diagnosis or treatment. Subsequently, if the program were presented with another patient displaying the same set of symptoms, the program fired the same set of rules. The program did not remember having previously seen a similar patient. One might state that this observation is of little consequence beyond some argument for computational efficiency. However, efficiency can be a significant concern in many situations. Moreover, a program without a memory cannot remember its mistakes and, thus, is destined to repeat them.

> Third, rule-based systems were not robust. If a problem were presented to the system that did not match any of the rules, the program could not respond. The system's knowledge-base was limited to its rules, so if none of the rules could apply, the system had no alternatives. It was brittle."
>
> [Slade 91, pp. 48 - 49]

According to researchers in the field case-based reasoning, the core of human expertise is experience [Riesbeck 89, Slade 91]. The rules that experts use are distilled from several cases that they have had opportunities to experience or witness. Thus even this general rule had its genesis in experience. Therefore, the foundation of knowledge is the case and not the rule [Riesbeck 89, Slade 91].

From the above discussion, it is clear that CBR is well suited for the development of experience transfer systems geared towards aiding project personnel in problem-solving tasks on construction projects. There are four reasons why this is so. Firstly, given the highly unstructured environment in which construction projects are executed, it would be difficult to abstract and generalize the problem-solving methods of an expert. Furthermore, generalizations are "impoverished compared to the original experience," are never perfect and there is always the danger of losing some important piece of information [Riesbeck 89]. Secondly, it would be rather difficult to find people with the required experience in construction willing and able to perform such generalizations. Thirdly, construction is a highly experience-dependent field, i.e., people rely quite heavily on prior experience to solve problems. Finally, people find it easier to narrate incidents or experiences rather than abstract from and express these experiences in the form of generalizations or rules. In the words of Riesbeck and Schank:

> "It is very difficult to remember an abstraction, but it is easy to remember a good coherent story."
>
> [Riesbeck 89, p. 7]

3.4. Roles of the Case-Based System and Human User in Problem Solving in Construction

For reasons cited in paragraphs 2.2.1 and 3.3, the initial goal of this research was to develop an experience transfer medium as a pure decision-aiding system. The role of the computer-based system was retrieval of relevant information and the presentation of the retrieved cases in a format convenient for user perusal. The user would browse through the retrieved cases and apply it to solve the problem confronting him or her after performing the required adaptation. However, as will be seen in Chapter 6, this strategy evolved and was modified during the course of the research to include adaptation. The user still has the responsibilities of (a) selecting the case that would be adapted, and (b) deciding whether the adapted case brings him or her to the final solution or closer to the final solution. The system would aid the user in the process of selecting the right case for adaptation by rank ordering the retrieved cases on the basis of degree of relevancy to the problem situation. In such a configuration, the computer-based CBR system plays a more active role in problem solving than pure decision-aiding systems like ARCHIE-2, CLAVIER (production version) and BATTLE PLANNER discussed earlier in this chapter.

4

HYPERMEDIA

4.1. What is Hypermedia?

Many people now feel that the information age will be dominated by hypermedia systems which are expected to support all conceivable media types, combining and integrating them as necessary for individual applications [Rosenberg 92]. During the last decade there have been dramatic changes in the field of information technology. The decade has witnessed the advent of increasingly powerful microcomputers and workstations, world wide communication networks, optical disc and other mass storage media, interactive video technology, digitizing and scanning technology and recently hypermedia databases. These events have revolutionized the way information is generated, stored, retrieved and transmitted.

What is hypermedia? It represents the synthesis of different data formats such as text, audio, graphics, still images, motion video in one delivery platform. The forerunner of hypermedia was hypertext, which mimics the human brain's ability to access information quickly and intuitively by association. All traditional text, whether in printed form or in computer files, is sequential, meaning that there is a linear sequence defining the order in which the text is to be read. In contrast, hypertext is non-sequential and there is no single order that determines the sequence in which the text is to be read [Nielsen 95].

The variety of nodes and links that can be defined make hypertext a very flexible structure in which information is provided both by what is stored in each node and by the way the information nodes are linked to each other. Since the information stored in the nodes can be graphics, images, sound, motion video or text, the resulting structure is also called *hypermedia.* This thesis will use the terms "hypermedia" and "hypertext" interchangeably. According to Nielsen:

> "The traditional definition of the term "hypertext" implies that it is a system for dealing with plain text. Since many of the current systems actually also include the possibility for working with graphics and various other media, some people prefer using the term hypermedia, to stress the multimedia aspects of their system."
>
> [Nielsen 95, p. 5]

Hypertext presents several different options or paths to the users and the individual user can choose the path he or she wants to follow at the time of reading the text. This facility is the result of the author of the text establishing multiple streams of information instead of a single stream [Nielsen 95]. In addition to allowing users to pick and choose paths, hypertext permits the user to ignore some nodes while exploring other nodes in depth.

Since hypertext has gained in popularity in recent years, researchers have been trying to define what really constitutes hypertext. In addition to the node-link-node structure and user-controlled browsing of the information space described above, hypertext systems must possess a "backtracking" capability, i.e., when users follow links around the hypertext network, they can return to some previously visited node when needed. Assume that we are currently located in node C in Figure 4.1. If we had arrived at this node via the path A —> B —> C, then the backtrack command would take us to node B. A second backtrack command would take us to node A. If on the other hand we had jumped from node A to node C, then issuing a backtrack command at node C would take us to node A. However, there does not seem to be a general consensus in the hypertext community as to the precise definition of hypertext. Various researchers have suggested incorporating additions to the basic functionality requirements of hypertext. For example, Nielsen states that:

> ". . . Frank Halasz from Xerox has put forward the view that a true hypertext system should include an explicit representation of the network structure in its user interface. . . . in most current systems that network is only present inside the computer. At any given time the user sees only the current node and the links leading out from that node; it is up to the user's imagination to picture how the entire network is structured."
>
> [Nielsen 95, p. 4]

In Halasz's view, the user should be presented with a dynamic overview showing the structure of this network. This is difficult to accomplish in practice because of the need to display thousands of nodes and the space constraints imposed by standard computer monitors.

Another suggestion is the use of bi-directional links in hypertext, meaning that the system should be able to display incoming and outgoing links from a particular node. Almost all current systems are limited to providing unidirectional links going outwards from a particular node, i.e., the user will be shown only where you can go next but not in what alternative ways you might have arrived at the current node [Nielsen 95].

Yet another requirement that has been suggested is access to remote databases over local area networks (LANs) and international networks. Access to remote databases will become a necessity in the near future, "since nobody can have all the world's literature stored on their own local computer no matter how big an optical disk they get. . . . . many hypertext systems are limited to working with data stored on a single personal computer. The main exceptions are the World Wide Web which works across the entire Internet and technical documentation systems like Sun's Answerbook which work across a corporate network" [Nielsen 95, p. 3].

It is also said that true hypertext should also make users "feel" that they can move freely through the maze of information available. This means short response times and low cognitive load when navigating, i.e., "users do not have to spend their time wondering what the computer will do or how to get it to do what they want" [Nielsen 95, p. 5].

4.2. Basic Hypertext Structure

The hypertext structure consists of a network of pieces of information called nodes) and logical links between the pieces of information. The links are basically pointers to other pieces of information. Figure 2 represents such a hypertext structure with nodes and links.

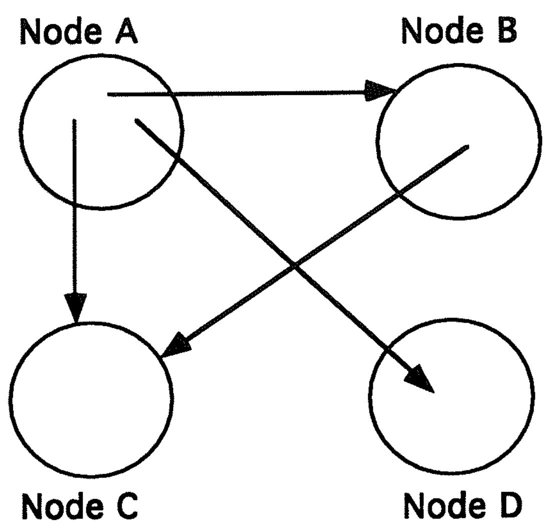

Figure 4.1. Hypertext structure showing nodes and links

Researchers in the field of hypertext have suggested a standardization of the architecture of hypertext systems. Although there is no such standard model existing at present, hypertext systems can be visualized as consisting of three levels [Campbell 88]:

1) Database Level

2) Hypertext Abstract Machine (HAM) Level

3) User Interface Level

4.2.1. The Database Level

The database level (see Figure 4.2) is at the bottom of the three-level model and deals with the traditional database issues such as storage, shared data and network access, multi-user access to information, and various security considerations, including backup [Nielsen 95]. Hypertext systems typically store large volumes of information on various computer storage devices like high-capacity hard disks, optical disks, etc. Quite often some of the information has to be stored on remote servers and is accessed over networks like LANs, Internet, etc. Irrespective of the method used to store the information, the system should be able to retrieve a specified chunk of information in a very short time.

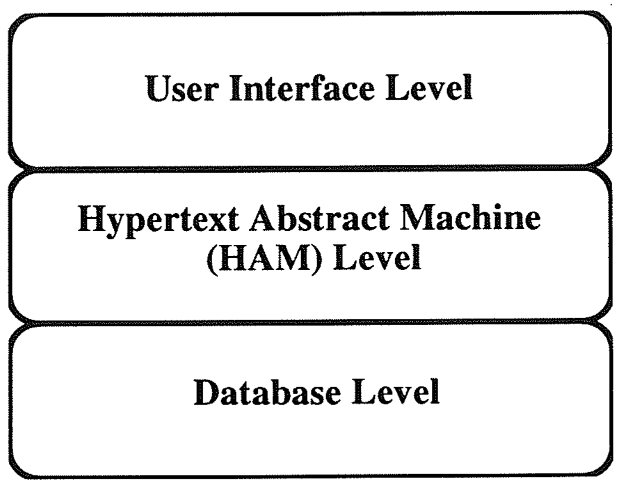

Figure 4.2. The three-level architecture suggested as a standard for hypertext systems (Adapted from Campbell 88).

4.2.2. Hypertext Abstract Machine (HAM) Level

As shown in Figure 4.2, the HAM is sandwiched between the database and user interface levels. It is at this level that the hypertext system determines the basic nature of the nodes and links and where it maintains the relations among them. The HAM should have knowledge of the form of the nodes and links and should know what attributes were related to each. For example, a node may have an "owner" linked to it that stored the details of the user who created it and who has to authorize changes to be made to the information stored.

Another important aspect of information handling by hypertext systems is the ability to transfer information from one hypertext system to another [Nielsen 95]. Transferring hypertext is more difficult than simply transferring the information stored in the nodes. This is because hypertext transfer requires the transfer of linking information in addition to the text. Large parts of such "linking" information are likely to be lost due to the transfer [Nielsen 95]. For example, some hypertext systems like Intermedia have links that point to specific text strings in the destination node, whereas other systems like Hyperties only point to the destination node as a whole entity. A transfer of information from Intermedia to Hyperties could therefore result in the loss of important linking information.

4.2.3 The User Interface Level

The user interface deals with issues concerned with the presentation of information including such issues as what commands should be made available to the user, how to display nodes and links, and whether to include overview diagrams or not. For example, if the HAM level of a hypertext system defines the links as being typed, the user interface level might decide not to display that information at all to some novice users and to make typing information available only in an authoring mode. This distinction between reading and writing is one of the basic user interface issues. Similarly, if the user is to be provided information about link typing, then the user interface might do so by changing the shape of the cursor or show each link type in different colors if a color display is available.

4.3. Relevance of Hypermedia to Construction Experience Transfer

The issue of relevance of hypermedia to construction experience transfer can be discussed from the broader context of its relevance to the use of information in general, irrespective of the field, and its contribution to increasing the power of information technology to effectively capture, store and transfer such information. The subsequent paragraphs examine the issue of relevance under the following headings:

4.3.1. Flexible and Semantic Linking of Information

The significance of hypermedia in the modern information age was first envisioned by the American computer scientist Vannevar Bush [Cotton 93]. Most of Bush's ideas on the development and role of a "memory extension" system he called "Memex" form the basis for the development and use of hypermedia today. The foundations of the "Memex" system lay in associative indexing — the ability to link microfilm information together in ways that were meaningful to the user. Bush realized the potential and the consequences of the information explosion of the nineties and felt that existing indexing techniques were forcing researchers to "trace their requirements by following rigid alphabetical or numerical classifications."

He noted that:

> "The human mind does not work that way. It operates by association. With one item in its grasp, it snaps instantly to the next that is suggested by the association of thoughts, in accordance with some intricate web of trails carried by the cells of the brain."
>
> - Vannevar Bush (Source: [Cotton 93])

This method of accessing information is in sharp contrast to the traditional database approach where a high level data definition language and query language impose rigid structures on the way information is stored and retrieved respectively. For example, we might have records of five thousand concrete mix designs in a database maintained by a ready-mix concrete supplier, all of which have the same fields for the compressive strength of the mix, cement content, water content, coarse-aggregate content, etc. A hypertext information base has no central definition and no regular structure. We might have five thousand principal nodes for each of the five thousand mix design cases, but with the added advantage that some of the nodes can have a large number of links emanating from these nodes to secondary nodes while others are sparsely linked. Some mix design cases may have peculiar circumstances that affected the design while others did not. Likewise, tertiary nodes linked to the nodes containing contextual information could contain information that elaborate on the contexts. Using hypertext, authors would no longer have to tailor their work to suit the "average" reader. They could include any level of detail, and allow the *reader*s to decide how deep into the subject they want to go.

> "In general, the structure of a hypertext network is defined as a union of the local decisions made in building each of the individual nodes and links. Each link is put in because it makes sense in terms of the semantic contents of the two nodes it connects and not because of some global decision."
>
> [Nielsen 95, p. 11]

4.3.2. Augmentation of the Human Intellect

Problem solving on construction projects is being conducted in increasingly complex and unstructured environments. This, coupled with the relatively primitive reasoning capabilities of present day computers when faced with real-world situations they are not programmed to deal with, form two major obstacles to real-world problem solving on construction projects. Until such time that researchers in the field of computer science are able to develop the wherewithal to create systems capable of such problem solving, an effective alternative would be to use the computer in the role of an intelligent information provider rather than an active problem solver.

In the early 1960s, Douglas Engelbart conceived the idea of such a computer-based system for the "augmentation of man's intellect." The idea was to combine contributions from a human user consisting of ". . . the ability to organize, a knowledge of procedures, customs, methods and language, and skills, knowledge and training . . . with a 'tool system'. This would include capabilities for communicating with other users, for 'traveling' through an information space, for viewing information in a variety of ways, and for the retrieval and processing of information in a number of different media. . . such a system creates a synergy between the user and the computer that will amplify the user's intellectual capabilities. As a graphic demonstration of what happens when tools handicap our thinking, instead of augmenting it, Engelbart has suggested that we try to write with a pencil tied to a brick. Such a poor tool 'disaugments' our intellect" [Cotton 93, p. 23].

In summary it could be said that hypermedia allows us to explore a subject area from many different perspectives using a powerful and flexible medium that utilizes the full potential of the computer to store, retrieve and display information in the form of pictures, text, animation and sound until we either find a problem-solving approach that is useful to us or formulate one based on our understanding of previously recorded problem-solving approaches used under similar conditions in the past.

4.3.3. Semantic Compression and Managing Complexity

The long-term goal of hypermedia as envisaged by pioneers in the field like Bush, Engelbart and Nelson was that hypermedia should "serve as a communication medium, enabling us to communicate ideas about complex situations with elegance and simplicity using most if not all of our senses, and as a tool for managing complexity by allowing us to assemble and manipulate a mass of disparate multi-sensory information elements until they fall into patterns that make sense" [Nielsen 95, p. 38].

An important aspect of hypermedia is semantic compression. According to Cotton:

> ". . . one simple action, the equivalent of the smallest unit recognized by a computer (the binary 'on off'), would require a lengthy explanation if put into words, and still might not convey the same depth of meaning. Hypermedia, with its multi-sensory capabilities, offers us the opportunity to develop a similar 'economy of means' with which to express and compress large amounts of information. Semantic compression is necessary because it is only by using simple, elegant means of expressing complexity without violating variety and diversity that workable solutions will be found to problems that confront society."
>
> [Cotton 93, p. 38]

4.3.4. Usability

To be accepted in the real world, any computer-based experience transfer medium has to conform to standards of usability. Since a major part of user-interaction with the computer-based experience transfer system is likely to be with the hypermedia component of the system, the usability of hypermedia gains added significance.

Usability is traditionally associated with five usability attributes [Nielsen 95].

(a) Easy to learn

(b) Efficient to use

(c) Easy to remember

(d) Few errors

(e) Pleasant to use

In addition to the attributes mentioned above, usability has to be examined from two different perspectives: (a) the usability of the hypertext engine, i.e., the usability of the basic presentation and navigation support available, and (b) the usability of the contents and structure of the information base. Furthermore, the usability perspective will be different for end-users (readers) than for authors in many instances. The following paragraphs will discuss the usability attributes of the hypermedia component of the experience transfer medium.

(a) Easy to learn

For end-users: The functioning of the hypertext engine itself is easy to understand. Users are able to quickly learn the most basic commands and navigation options, use them to browse the hyperbase and locate the information required. When users enter the information base for the first time, they are immediately able to understand the first screen and browse from it.

For authors: Generally, the "easy to learn" attribute is of less importance for a hypertext author who typically will have to spend a lot of time with the system in order to deliver a quality end product. Authors who are editing an information base constructed by other authors can easily understand the basic structure of the information base and are able to modify it [Nielsen 95].

(b) Efficient to use:

For end-users: Well authored hypermedia systems generally afford relatively quick and easy access to required information if such information is present in the information base. When users arrive at a node, they are quickly able to orient themselves and understand the relevance of the node in relation to their point of departure (the node they came from) in terms of the information contained in these nodes.

For authors: Once the material that has to be put into hypertext format is available and the overall organization of this information in terms of the nodes and linkages is mapped out, authors can construct a hypertext structure relatively quickly.

(c) Easy to remember

For end-users: After a period of not having used the hypertext system, users have no problems in remembering how to use the hypertext engine or the hypertext information base. Furthermore, users can transfer their knowledge of the use and navigation of one information base to the use of another information base with the same engine. Although using a different engine would involve learning the subtle nuances of that engine, an experienced hypertext user will not experience much difficulty in the new environment.

For authors: When a hypertext structure needs revision after some time, it is easy for the author to return to the information base and update it. The author can remember or is reminded about the basic structure of the information base and does not need to commit to memory details in order to update it [Nielsen 95].

(d) Few errors:

Users will occasionally follow a link only to discover that they really did not want to go to wherever the link leads. This is likely to occur more frequently as a result of poor authoring rather than errors on the part of the end-user. In case users have erroneously followed a link, it is easy for them to return to their previous location. Users can in general easily return to locations previously visited by them (e.g., by using the "History" menu) in case they decide that some lengthy digression should be abandoned [Nielsen 93].

(e) Pleasant to use

On this topic Nielsen states:

> "Users prefer using the hypertext system to existing alternatives such as paper or other, non-hypertext computer systems. Users are rarely frustrated with using the hypertext engine or disappointed about the result of following links. Users feel that they are in control with respect to the hypertext and that they can move about freely rather than feeling constrained by the system."
>
> [Nielsen 95, p. 284]

Finally, information technology, often loosely defined as "computing plus telecommunications," is fast becoming a prerequisite for firms to compete effectively in the modern business world. The construction industry is no exception. Hypermedia presents the "human face" of information technology to the end-user and could be the solution to the problem of "disembodiment of work" resulting from a "sense of alienation and powerlessness" that can result from people constantly interacting with abstract representations of real-world things like beams, slabs, columns, etc. on a computer screen [Cotton 93, p. 34].

5

THE HYBRID SYSTEM

Section 5.1 briefly discusses the predominant methods of information retrieval in hypertext, notes some drawbacks with these methods, and outlines techniques employed to mitigate the effects of the drawbacks. It thus lays the foundation for the development of a rationale in Section 5.2 for the use of CBR in conjunction with hypertext for information retrieval. Section 5.3 discusses the conceptual configuration of a hypertext system followed by the development of a system architecture for the hybrid experience transfer system in Section 5.4. The final section of this chapter lists some of the major advantages and disadvantages of the hybrid system.

5.1. Information Retrieval in Hypertext Systems

Although the unstructured network representation of ideas has gained popular support as a generic model for hypermedia systems, searching for information purely by navigation or browsing is not efficient in all situations. Navigation is a good method for searching information spaces that are small enough to be covered exhaustively and are familiar enough to the users to let them find their way around the network of nodes. Unfortunately, many information spaces in real life are large and unfamiliar to users and require the use of queries to find information [Nielsen 95].

When users move around a large information space using pure navigation, there is a real risk that they may become disoriented or have trouble finding the information they need. This phenomenon is called "loss in hyperspace" by researchers in the hypertext community. There have been several solutions suggested to the navigation problem. The most simple of these being the use of guided tours through the information space, avoiding the necessity for user-directed navigation. However, this solution comes with a price. According to Nielsen:

> "Guided tours are nice, but they really bring us back full circle to the sequential form of information. Even though guided tours provide the option of side trips, they cannot serve as the only navigation facility since the true purpose of hypertext is to provide an open exploratory information space for the user."
>
> [Nielsen, p. 249]

Another commonly used solution to the navigation problem is the use of overview diagrams. A hypertext user utilizes overview diagrams in the same way that a tourist uses maps. The tourist metaphor is an apt one because hypertext users are mostly supposed to find their own way around the information space just as a tourist has to find his way around a new city with the aid of maps. The problem with overview diagrams is that they can be shown only one screenful at a time and very large information spaces would require a meta-navigational mechanism. Meta-navigation can be achieved in several ways. Some of the more common methods are (a) using a zoom facility that allows users to see the information in more or less detail, (b) moving a viewport indicator over a reduced representation of the main overview diagram, and (c) fisheye views that can show the entire information space in a single overview diagram using varying levels of detail [Nielsen 95].

The simplest search method used in current hypertext systems is full text search which finds occurrences of words specified by the user. Some hypertext systems simply take the user to the first occurrence of the search term (e.g., HyperCard). The problem with this method is that the user has no way of knowing how many other hits there are in the hypertext without actually visiting each one of these hits. It is much better to display a menu of the hits and let the user decide whether the query needs further refinement to narrow the choices or select one of the hits presented. With faster computers it is becoming possible to perform dynamic queries where the users specify desired search values by manipulating sliders or other controls and get feedback from the system in real time [Nielsen 95]. The feedback from the system informs the user whether the search terms are reasonable even as they are being formulated and specified.

Even though most query systems perform text searches or select objects based on numeric attribute values, it is also possible to search on other types of media.

> "Since humans are visually oriented, they often rely on images to remember things, and image-based searches might well be a very useful supplement to text and attribute-based search."
>
> [Nielsen 95, p. 228]

Unfortunately, the capabilities of present-day computers in the field of pattern recognition are very limited and they do not understand pictures as well as they do ordinary text. The traditional method of searching a database of images is to specify the text caption or keyword with which an image has been annotated. A few experimental systems [Hirata 93] have been developed that allow computers to deal with image understanding at a very rudimentary level. In such systems, the user can either sketch the approximate composition of the image or select an existing image and use it to link to more images of the same kind. The system uses pattern recognition to establish links between images that look approximately the same (e.g., all photographs of tall buildings).

A very promising method of making search more effective is to display the search results in an overview diagram by highlighting those nodes that contain hits. Examples of such systems are the FSN system [Fairchild 93], which highlights search hits in a three-dimensional overview of an information space, and SuperBook [Egan 89], which annotates the names of nodes with the number of hits to allow users to see not just *where* there is something of interest but also *how much* there is. This method of displaying the results of a search can provide clues as to how interesting a given region of the information space is to the user.

5.2. Combining CBR with Hypertext

Although most present-day hypertext systems have user-directed navigation complemented by query-based search capabilities for retrieving information, they have two major shortcomings when viewed from the perspective of a medium for the transfer of construction experience.

Firstly, it would be extremely difficult to perform similarity-based retrieval using the available information retrieval capabilities of current hypertext systems. Consider a hypothetical situation in which concrete on a site must be transported by an inclined conveyor. This situation requires the design of a mix that is capable of being transported on an inclined surface. Let us also suppose that no mix design in the case-base caters to this need. To perform the kind of similarity-based retrieval required, the system must be able to infer that, among the mixes known to the system, the one used for concreting a hopper-shaped bottom of an elevated water-tank is most similar to the mix required with regard to satisfying the transportability criterion of the current situation. This involves the incorporation and use of domain-specific knowledge within the system.

Secondly, the system must be capable of more than just playing the role of a passive information provider. The information retrieved may, more often than not, only partly meet the needs of the current situation. This implies that the system must have the capability to at least partially adapt the information retrieved to suit the requirements of the current situation as much as possible.

From the preceding paragraphs it is clear that what is required are enhancements of the current capabilities of hypertext systems in terms of accuracy of retrieval and adaptation of retrieved information. From the discussions in Chapter 3, it appears that CBR could provide the required enhancements.

5.3. Configuration of the Hybrid System

Technology has had a major impact in improving the power and efficiency of traditional experience transfer media. Each medium has a specific set of circumstances in which it would be most suitable. For instance, a foreman who needs to instruct his crew on the execution of a task to solve a problem which has suddenly cropped up would prefer to use face-to-face discussions with his crew and the superintendent on site as the medium rather than video-conferencing, while a CEO discussing company policies with project managers on different project sites would perhaps prefer video-conferencing. Figure 5.1 shows the methods of experience transfer, traditional media used in the transfer of experience in construction, and recent trends in such media. The intention here is not to suggest the total replacement of any of the traditional media but rather to encourage a rational use of the power of modern computer technology in the transfer and utilization of construction experience in appropriate contexts.

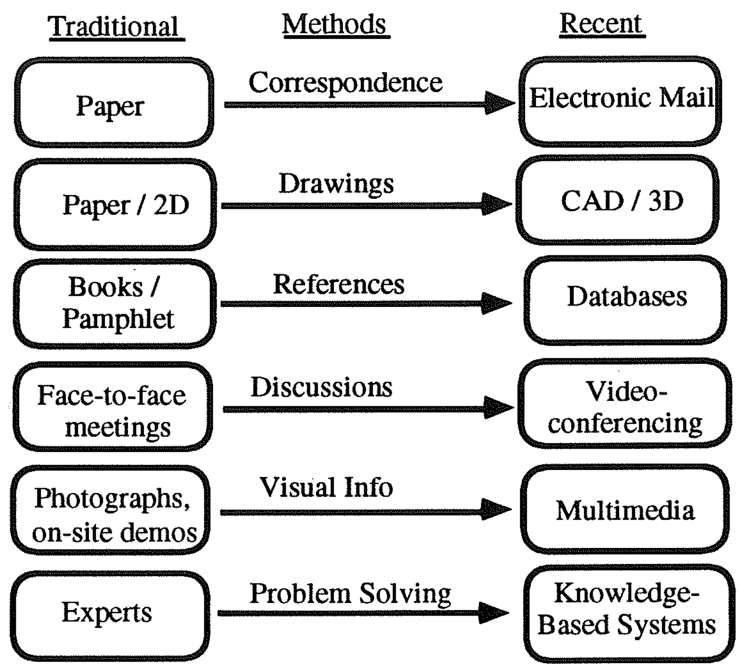

Figure 5.1. Methods of experience transfer, traditional experience transfer media and recent trends in these media.

The system proposed here is a hybrid decision-aiding system which combines the powerful, sensory-rich presentation capabilities of a multimedia information-base with the reasoning abilities of a case-based system. Figure 5.2 shows a graphical representation of the hybrid-system approach where the synergy developed by the interaction between the hybrid CBR-hypermedia system and the human will be used to solve problems.

The sheer volume and complexity of the information that needs to be stored, conveyed and used for problem-solving on future projects makes traditional media used in construction inadequate. As discussed in Chapter 4, hypermedia is a rapidly developing computer technology that supports active user interaction with various media, and facilitates the manipulation and integration of information stored as text, graphics, animation, sound, still pictures, and video in these media.

Dramatic technological advances in the fields of mass storage devices, digital video compression, high capacity (large bandwidth) networks, hypermedia application software, high quality graphics, high-resolution visual display devices, high-fidelity sound, and faster and more powerful CPUs have made the hypermedia revolution possible. There is also a general feeling among experts in the field of information

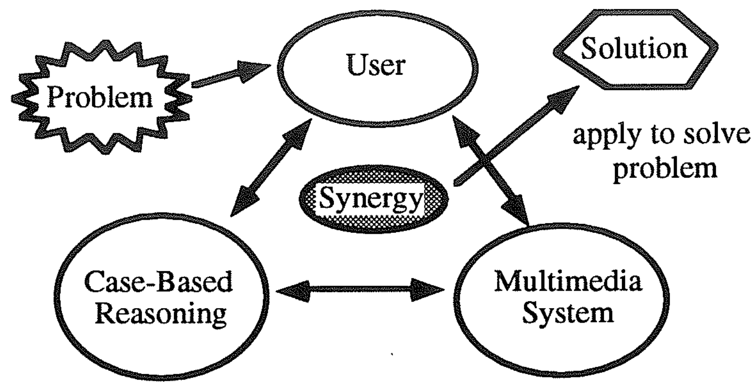

Figure 5.2. The synergy developed by the interaction of a hybrid knowledge-based system with a human user can be applied to solve and predict problems.

technology that the information age will be dominated by hypermedia systems and whole computer companies are betting their futures on hypermedia [Rosenberg 92].

While the CBR component of the hybrid system will function as the retrieval component of the system and retrieve the most relevant cases sorted in the order of the relevancy of the retrieved cases to the current problem situation, the hypermedia component will contain the bulk of the information with facilities for the user to access and navigate through the network of information presented in a variety of forms. Most of the difficult decision making tasks will be left to the user. However, the user has the option to select one of the retrieved cases and request the system to perform adaptation to the extent possible. Thus the user can either use the retrieved cases or the end product of adaptation in formulating his or her decision.

As an example of the use of a retrieved case without adaptation in decision making, consider a situation where a site engineer has to decide on the most appropriate method of dewatering a basement excavation on a particular project. The problem is presented to the system. The user will be presented with a list of cases sorted by the degree of relevancy of the cases to the current situation. By selecting one of the choices presented, the user will be taken to the details of the case presented in hypertext or hypermedia format. Clicking on highlighted words in the text (e.g., well-point system) will take the user to a still picture showing the layout and deployment of the well-points, pumps, pipelines, etc., on a previous project. Similarly, the user could be shown video segments of the system in operation and the state of the excavation site, surroundings when the problem was first encountered, and its state after the well-point system of dewatering was adopted. Similar perusals of other retrieved cases could be made if needed. The user now has information about the dewatering methods used under different conditions, which of the methods were successful, problems encountered when employing these methods, the tools, equipment and personnel required, the availability of these resources, etc. The knowledge which was once privy to some of the most experienced engineers in the organization is now available to him. It is now a matter of using the new knowledge gained in coming up with a viable solution to the problem.

Figure 5.3 shows how a hypermedia system can be used as a comprehensive medium that possesses the functionality of each of the other media identified in the figure. It is this multiple-functionality characteristic that enables it to function as a single homogenous experience transfer medium that subsumes most other traditional mediums used for the transfer of construction experience.

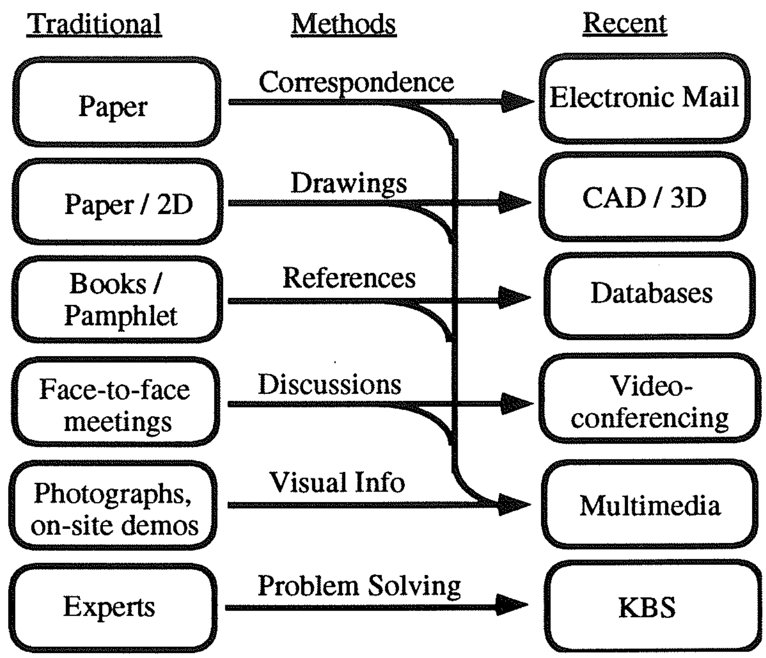

Figure 5.3. Multimedia can function as a single homogeneous medium incorporating many different methods of experience transfer.

5.4. System Architecture

For two reasons it was felt that rather than developing the entire system from scratch it would be better to develop the system by achieving a seamless integration of off-the-shelf software: (1) savings in time and effort, and (2) availability of sophisticated, relatively low-cost CBR and hypermedia software for the Macintosh computer.

The core of the CBR component of the hybrid system is REMIND, the CBR shell from Cognitive Systems, Inc. It is a knowledge-engineering shell which facilitates the development of applications using case-based technology [CogSys 93]. The shell allows the programmer to design case representations, enter prior cases into a case library, set up retrieval mechanisms, and develop a user interface for the presentation of the retrieved cases to the end user. The user can then enter information about the current design problem, specify a retrieval method, and retrieve similar cases from memory. The shell also provides the means for adaptation rules to be built into the system.

The hypermedia component will be built around a hypermedia shell like HyperCard. HyperCard provides the tools necessary to build a hypertext system, is easy to learn and allows for rapid prototyping of applications. However, from the perspective of the development of the hybrid system, it facilitates the development of high quality Graphical User Interfaces (GUIs) and the integration of various sub-components like a video-module or an audio module to the system. Furthermore, links to other applications can be created from a GUI, and an in-built programming language called HyperTalk facilitates the development of computational hypertext where information is generated at read-time under program control.

The CBR component interfaces with the GUI through an Application Program Interface (API). Each multimedia application module will be linked to the GUI separately, thus ensuring modularity. User interaction with the system will be through the GUI. The API will facilitate communication with the CBR shell transmitting user requests for information to the CBR shell and sending information retrieved by the CBR shell back to the GUI to be presented to the user. The system architecture is shown in Figure 5.4. Please note that, although the hypertext module is shown distinct from the GUI in the system architecture, it is developed using the same application software that is used for developing the GUI.

5.5. Advantages and Disadvantages of Hybrid System

This section lists the advantages and disadvantages of the hybrid system from the organizational and functional perspectives.

The advantages of such a hybrid CBR/hypermedia system are:

(a) It possesses the collective experience of several experts.

(b) Project personnel will not feel that they are perceived as inefficient or incapable of delivering the goods.

(c) Even experts themselves could consult the system because it contains the knowledge of other experts.

(d) There is no disruption of work.

(e) Problem-solving methods that worked on previous projects, why they worked, failures and the causes of such failures can all be observed, studied and understood in great detail in a sensory-rich hypermedia format instead of in abstract oral descriptions of an expert.

(f) It maximizes the use of the strengths of each of the three components in the system; i.e., the retrieval and adaptation capabilities of CBR, the sensory rich presentation capabilities of hypermedia, and the reasoning abilities of the human user. Furthermore, each component makes up some of the deficiencies inherent in the other two components. For example, a human user has a relatively small store of cases in long-term memory, is not always good at

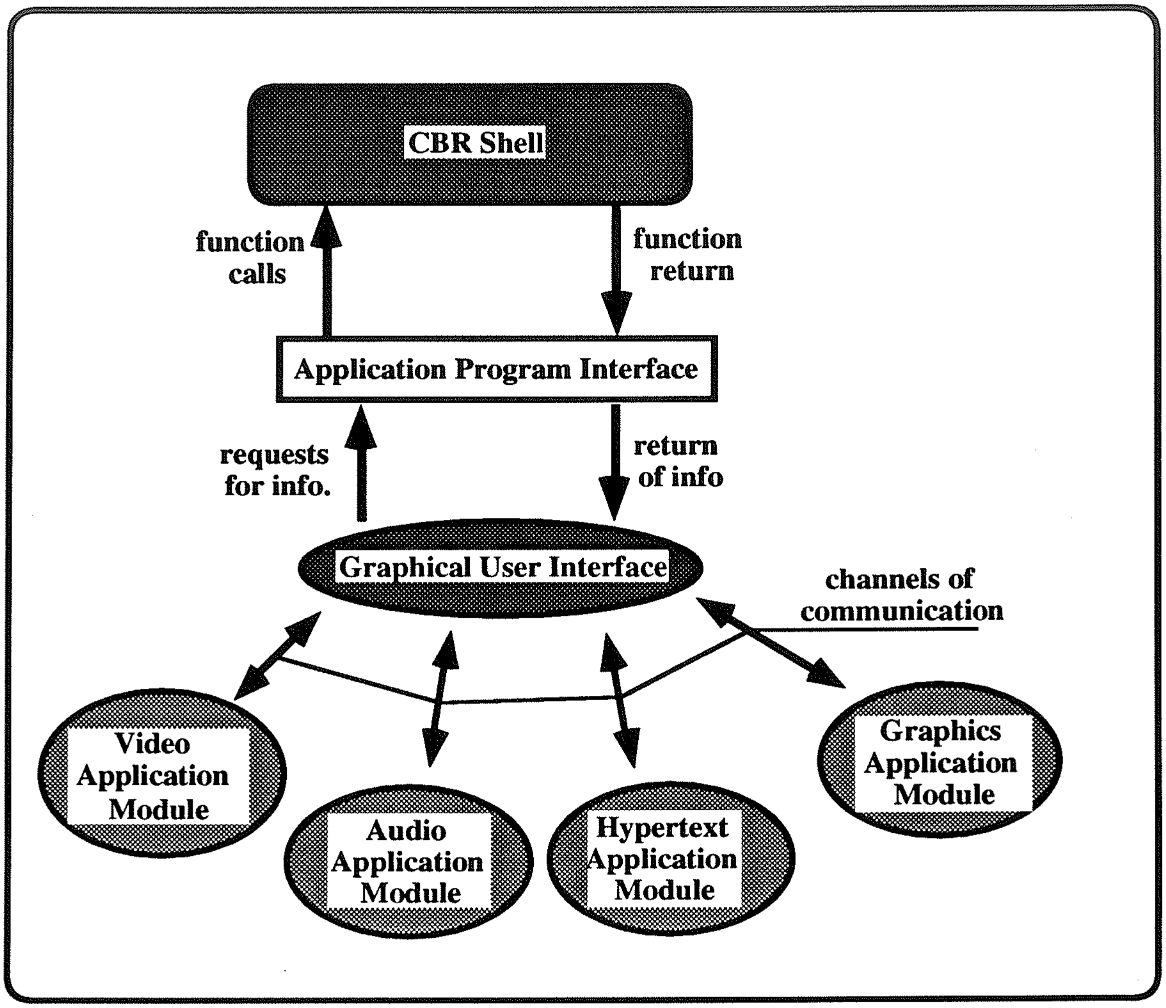

Figure 5.4. System architecture of the hybrid CBR/hypermedia construction experience transfer medium.

retrieving the most appropriate case, and specific details of cases often fade from memory. However, the CBR component can retrieve the most appropriate case with much more consistency than a human and store a far greater number of cases. The hypermedia component can present the cases to the user with no loss of information even after many years.

The disadvantages of the system are:

(a) Each project must have its own knowledge acquisition cell to recognize and capture information that has the potential to be used on future projects.

(b) Gathering information in hypermedia format can be expensive, and cumbersome within the confines of a construction project.

(c) A certain degree of expertise and maturity of judgment is needed in the recognition of cases that have to be captured.

(d) Cases worth capturing may not present themselves everyday and top management may consider the waiting period between recording of cases as a waste of valuable man-days of the personnel assigned to the experience capture cell.

(e) It may be economically justifiable only in large projects.

This chapter presented some of the shortcomings of information retrieval in hypertext systems and discussed how the hybrid computer-based system could overcome these shortcomings. This was followed by the development of a conceptual configuration and a system architecture for the hybrid system. The next step was to design, implement and test the hybrid computer-based system. Since the development and testing of such a system is beyond the scope of a single thesis, one component was selected for final development and testing. Chapter 6 will present a scheme for testing the critical component of the experience transfer medium. It will present details about the component selected, the rationale for the selection of the component and the domain in which the system will be implemented.

6

Case-Based Design Of Concrete Mixes

This chapter discusses the rationale and scheme for the creation of a test bed for trying out the ideas and concepts developed in Chapters 1 through 5. Section 6.1 presents reasons for the selection of the CBR component of the hybrid system for development and testing of the prototype. Section 6.2 details the motivation for using the CBR paradigm in designing concrete mixes. Section 6.3 details the purpose, scope and objectives of prototype development and testing. Section 6.4 outlines the theory underlying concrete mix design. Section 6.5 develops the point of departure of the prototype development activity. Section 6.6 discusses the impact of Case-Based Design on the state of concrete technology.

6.1. Selection of Component for Prototype Development and Testing

While each of the two computer-based components in the hybrid experience transfer system have a role to play in problem-solving, a decision was made to select the most critical component for prototype development and testing in order to limit the scope of the research. The critical aspect from the perspective of the development of such a system appeared to be the functioning of the CBR component for the following reasons:

(a) The quality of decision-making depends on the availability of information from past projects that is relevant to the current problem situation. In the hybrid decision-aiding system, it is the CBR component that is responsible for retrieving such information from memory in the form of cases and rank-ordering them by the degree of relevancy of the retrieved cases to the current problem situation.

(b) It is the CBR component that contains the reasoning capabilities needed to adapt the retrieved case to meet the demands of the current situation. Such adaptation presents the user with information that could put him in closer proximity to the solution than unadapted retrieved cases.

(c) To the best of the author's knowledge, there has been no work done in utilizing CBR for designing concrete mixes. As a consequence, developing indexing and adaptation schemes are uncharted research areas and pose significant challenges.

(d) Although CBR is conceptually a simple paradigm, it is still in its infancy and technical expertise in the field for consultation and guidance is relatively scarce. Furthermore, the author has had experience in the development and testing of hypermedia systems [Paulson 92].

6.2. Motivation for Use of Artificial Intelligence in Design of Concrete Mixes

Concrete is one of the most widely used construction materials in the world. Almost 7 billion tons of concrete are produced world wide every year [Mehta 94]. According to the Civil Engineering Research Foundation (CERF), an affiliate of the American Society of Civil Engineers (ASCE), the annual production of concrete in the United States alone is estimated to be 500 million tons. All indications are that it will continue to be an indispensable material and will be used in greater quantities than any other man-made material in the field of construction in the future [Mather 94]. In spite of the heavy demand and large-scale use of concrete, the field of concrete technology has not experienced the spectacular progress seen in other areas of science and technology. Among the visions of CERF is that:

> "Intelligent systems will aid in the selection of concrete with the desired performance characteristics for each intended application."
>
> [Mather 94, p. 33]

Traditionally, concrete mix design has been a process which involves generating an approximate design description followed by the application of a trial-and-error procedure to arrive at the final design description. The process is cumbersome and expensive. The efficiency of the mix design process depends to a large extent on the experience and material-specific knowledge of the designer. Firms which specialize in the manufacture and supply of concrete have tried to address this problem by adopting a design-by-selection approach. It involves storing past mix design cases in a database — more like a catalog of pre-existing designs. When a new customer request comes in, they look through this catalog, that is, the database is queried and the retrieved case is used to manufacture the mix. The problem with this approach occurs when customer specifications do not match any previous mix design stored in the database. In such instances, the firms have to resort to using the more traditional trial mixtures approach of designing the mix. Progress in the field of concrete technology as envisioned by organizations like CERF and informal discussions with representatives of the concrete industry (National Ready Mix Concrete Association, Northern California Concrete Association, Graniterock) academia, and construction firms (Guy F. Atkinson Co.) point to a growing awareness of the need to develop new and more powerful approaches to the design of concrete mixes.

Even after more than seven decades of research since the enunciation of Abrams' law and the formulation of a rigorous mix design procedure, concrete mix design is still largely being done by the trial-mixtures method. Although trial-mixtures methods of mix design like the excellent ACI 211.1 method have been principally formulated to accommodate the use of a wide variety of raw materials and the concomitant variations in material properties that have to considered, there seems to be no explanation so far in concrete technology literature as to the reasons for the apparent lack of emphasis on simulating the trials, i.e., by evaluating the mix design description against given criteria without recourse to the process of physically carrying out the trials. The vagaries brought about by the use of different materials do not completely account for this phenomenon. This fact is demonstrated by the lack of simulation capability in the mix design procedures employed by ready-mix concrete suppliers. Since simulation capabilities are critical to the development of more powerful approaches to concrete mix design, particularly knowledge-based approaches, it is imperative that we understand the obstacles to the development of such capabilities and explore the means to overcome these obstacles. The approach adopted by this research to gain such an understanding is through an in-depth study of the epistemological characteristics of the mix design domain. Unfortunately, there have not been very many research efforts aimed at such an in-depth analysis of the concrete mix design process or the use of techniques developed in the field of artificial intelligence in designing concrete mixes in particular.

6.3. Purpose, Scope and Objectives of Prototype Development

The main purpose of the prototype development is to investigate the feasibility of applying the retrieve-and-adapt approach used by researchers in the field of case-based reasoning to the design of concrete mixes. If successful, it will provide researchers and practitioners in the field of concrete technology with the basis of a mix design methodology that utilizes knowledge of the performance of prior mix design descriptions to arrive at new mix design descriptions to suit current situations.

6.3.1. Scope of Development Activity

The types of concrete that will be included in this activity will be normal-weight (approx. 4000 lb. / cu. yd.), medium strength (3000 psi to 6000 psi) concretes with and without air-entrainment. Although the emphasis will be on the strength and workability aspects of concrete, durability considerations such as exposure to freeze-thaw and exposure to sulfates will be included. Water-reducers, set retarders and accelerators will be the classes of admixtures that will be included. The methods of transporting and placing of concrete that will be considered are crane and bucket, buggies, conveyors, pumping and tremie.

The mix designs that would be researched and studied would be those designed and manufactured by ready-mix concrete suppliers and used on construction projects. Although the approach developed in this activity for the design of concrete mixes could be utilized by other designers of concrete mixes, it is primarily targeted for use by the ready-mix concrete industry.

6.3.2. Specific Objectives of Prototype Development Activity

- The primary objective of the activity is the development of an alternate approach to the current methods of designing normal weight, medium strength concrete mixes based on the retrieval and adaptation of mix design descriptions which have been successfully used in concreting work under similar conditions in the past. More specifically, the aim is to improve upon the design-by-selection approach to proportioning mixes through a process of retrieving and adapting prior mix design descriptions.
- The secondary objective is to identify (from available literature) or develop phenomenological models which will form the core of the knowledge required for adapting prior mix design descriptions to suit current contexts. The phenomenological models will be augmented by heuristic rules which will be developed based on discussions with experts in the field of concrete mix design.

6.4. Background

Arriving at mix design descriptions, also referred to as mix proportioning or mix designing, is a process of selecting suitable ingredients of concrete and determining their relative quantities with the objective of producing as economically as possible concrete of certain minimum properties, notably strength, workability and durability [Mehta 94, Mehta 86, Neville 81]. Concrete mix design methods have evolved from the arbitrary volumetric methods or prescribed mix methods (e.g. 1: 2 : 3 — cement : sand : coarse aggregate) of the early 1900's to the designed mix methods described in the American Concrete Institute's (ACI) *Committee 211 Standard Practice for Proportioning Concrete Mixes* and the *Design of Normal Concrete Mixes* of Building Research Establishment, U.K. [Kosmatka 88, Neville 87]. The ACI method is one of the more popular methods of designing concrete mixes in the world today [Bai 94].

The modern methods of mix design generally involve the use of trial mixtures to obtain the required composition of the mix. For instance, in the ACI 211.1 method of mix design, weights of water, cement, coarse and fine aggregates and the quantity of air entraining admixture are determined from tables or charts which are based on consensus (and usually approximate) knowledge. Several trial mixes are then made and tested for desired properties of the fresh and hardened concrete. The proportions are modified based on the results of the tests conducted on the trial mixtures and the process is continued until a mix with the desired performance characteristics is obtained. The tests generally involve taking slump and compressive strength measurements, visual observations, touching, prodding, passing a trowel over the mix sample, etc. The number of trials depends to a large extent on the knowledge and experience of the designer. The procedure is time consuming and cumbersome [Popovics 82] and has to be carried out by experienced personnel.

From the perspective of the development and testing of a CBR-based decision-aiding system for the design of concrete mixes, the point that has to be noted is that the mix design process is basically one of trial and error. The following paragraphs examine concrete mix design in the light of a more general model of design upon which most engineering systems are founded.

Design is a process which transforms a set of functions into a design description in such a way that the artifact being described by the design description is capable of producing these functions [Gero 90]. Function has been defined as the relation between the behavior of a system and the goals of a designer [Bobrow 84].

According to Gero [Gero 90, p. 28]:

> " In designing, behavior can be viewed in two ways. First is the behavior of the structure Bs (where Bs is a set), which is directly derivable from structure:
>
> S —> Bs (where S represents the structure and —> represents some transformation)
>
> . . . Transforming function to expected behaviors Be (where Be is a set) provides the second view of behavior.
>
> F —> Be (where F represents the function) . . .
>
> The predicted behavior of the structure (Bs) can be compared with the expected behavior (Be) required to determine if the structure synthesized is capable of producing the functions:
>
> Be <—> Bs
>
> where <—> is a comparison."

In concrete mix design, function is rarely specified. The specifications are mostly linked to the performance expected from the mix. In the terminology of the general design model, this corresponds to expected behavior. The required properties of hardened concrete are normally specified by the end user or the engineer and the properties of fresh concrete are governed by the type of construction and by the methods employed for transporting, placing and consolidating the concrete. Predicted behavior, however, is not so easily available. For example, it is not possible to predict from the mix design description whether a mix is workable.

Thus the knowledge that provides structure-to-performance mappings (interpretive knowledge in the nomenclature used by Coyne *et. al.* [Coyne 90]) in the concrete technology domain to simulate the performance of a design is sparse. Further, most of the knowledge that is available (in mix design codes and manuals) is formulated for the trial mixtures approach of mix design. This state of affairs in the domain could be attributed to the following:

Firstly, the highly heterogeneous and complex structure of concrete make it difficult to constitute exact models of the concrete structure from which the behavior of the material can be reliably predicted [Mehta 86].

Secondly, in the absence of knowledge of microstructure-property relationships the only option available is to rely on design-description-to-design-performance and design-description-to-function relationships. These relationships are macrostructure-property relationships. But even such knowledge as used in the modern practice of mix design is consensus knowledge (e.g., ACI mix design tables), is empirical in nature, is broad-based (does not apply to any specific set of mix design materials) and is founded on simplifying assumptions (e.g., ignoring the effect of aggregate grading on workability), which reduces the accuracy of the results obtained when such knowledge is applied in the mix design process.

Finally, there is the problem of the inadequate definition and measurability of workability. The term workability is a property that is familiar to engineers but is very difficult to define [Akroyd 62]. The natural tendency is to define it as an intrinsic property of fresh concrete. It is often used with modifiers such as "excellent," "good," "fair," and "poor". But such modifiers are of little value in the design of concrete mixes as their use expresses a personal judgment of how well or badly a given concrete mix behaves under the particular conditions of work. ASTM C 125 defines workability as the property determining the effort required to manipulate a freshly mixed quantity of concrete with a minimum loss of homogeneity. In other words, workability is the ease with which it can be mixed, transported, placed, compacted and finished without harmful segregation. The effort required to place concrete is mainly determined by the work needed to initiate and maintain flow. The amount of work is dependent on the rheological properties of the cement paste, the internal friction between aggregate particles and the external friction between the concrete and formwork and the concrete and reinforcement [Mehta 86]. Thus the term workability encompasses such characteristics as flowability or mobility, compactability, placeability, cohesiveness or stability and finishability. This clearly makes workability a composite property and is meaningful only when understood as representing not only the intrinsic characteristics of the fresh concrete but also extrinsic factors (work conditions) as well [Mehta 86, Powers 68].

A number of standard tests have been devised to "measure" workability. Some of them are the slump test, the compacting factor test, the Vebe consistometer test and the flow test. The most popular of these tests by far is the slump test. The standard tests individually and collectively have been criticized in concrete technology literature [Tatersall 76], but the most serious criticism is that any one of the standard tests is capable of classifying as identical in properties two concretes that are subsequently found to behave very differently in practice. For instance, it is a well known fact that two concretes of the same slump may be found to have quite different workabilities on the job [Neville 81, Tatersall 91].

The concept of workability is of great significance in concrete mix design. It is one of the key properties that must be satisfied regardless of the sophistication of the mix design procedure used. A concrete mixture that cannot be placed easily or compacted properly is not likely to provide the expected strength and durability characteristics. Unfortunately, even though the concept of workability is of paramount importance in determining mix design descriptions, there is no absolute measure of the concept which would enable it to be used in the mix design process.

In summary, concrete technology is a weak-theory domain [Porter 90]. The lack of sufficient structure-to-performance knowledge at both the microscopic and macroscopic levels coupled with the inability of the concrete technology community to come up with a useful, application-oriented definition of workability has resulted in the development of mix design methods which rely to a large extent on the preparation and modification of trial mixes to arrive at design descriptions that meet the required specifications.

6.5. Establishing Point of Departure from Related Work

It is clear from the discussion in section 6.4 that any attempt at making the mix design process more exact will be centered around a more accurate representation of the concept of workability and circumventing the problem of insufficient knowledge of the behaviors of the concrete mix and the components of the mix. The following paragraphs discuss these issues in the context of current mix design methods and how the current prototype development effort attempts to address these issues.

6.5.1. Workability

Since workability plays such a major role in the design of a concrete mix, it is imperative to factor in the workability concept as realistically as possible in the mix design process. Most of the current methods of mix design use the results of standard tests like the slump test or the Vebe test as rough measures of workability and factor in these measures into design tables. For instance, the ACI 211.1 method for design of normal concrete mixes provides a table that shows the slump as a function of the water content and the maximum size of the aggregate [Kosmatka 88]. The British method of mix design uses a similar approach and provides a table that shows slump and Vebe seconds as a function of the maximum size of the aggregate, the type of the aggregate (crushed or uncrushed) and the water content [Neville 87]. Unfortunately, as stated in section 6.4 above, the standard tests do not provide a sufficiently accurate or comprehensive picture of the workability of the mix. At the other extreme is the suggestion that more fundamental properties like plastic viscosity, mobility, yield, etc. be used as measures of workability [Tatersall 91]. This approach appears to be promising but is still in the research stages and it will be some time before the results of such studies are made available to the concrete technology community and adopted in practice.

This effort takes a different approach. As discussed in section 6.4 above, the concept of workability, as used in the standard methods of mix design, has a very limited interpretation outside the context of specific job conditions. This is one of the causes associated with the problem of reduced proximity of the computed design description to the final design description at the pre-trial mix stage. Therefore, one way of mitigating the problem is to take into consideration the workability requirements of a mix in terms of both intrinsic properties (e.g., slump) and extrinsic factors (e.g., formwork intricacy). This method of representing workability has the twin advantages of not only taking into consideration extrinsic factors influencing the design of the mix but also circumvents the problem of representing workability in absolute terms. Thus workability will be represented "implicitly" as a combination of design descriptions and job conditions which include those for transporting, placing, compacting and finishing. What is implicit in the representation is the relationship between workability requirements for a particular set of job conditions and the mix design description. This relationship or association will be based on what has worked before. For instance, if we know that for a project XYZ, mix design A has worked well, then we can associate mix design A with the job conditions that affect workability in project XYZ without explicitly stating the association.

6.5.2. Knowledge Level

The process of design is essentially one of arriving at a design description where the behavior derived from the design description matches the expected behavior obtained from functional or performance specifications [Gero 90]. In the domain of concrete technology this translates to an issue of the availability of knowledge in the form of relationships between:

a) Mix design description and performance of the concrete made with the mix

b) Functional specification and the performance required from the mix

In the field of concrete mix design, functional specifications are not common. Therefore relationships between functional specifications and performance are usually not required. The relationships relevant to concrete mix design can be obtained in the following forms:

(a) Artifact - property relationships (e.g., Prescribed mix - compressive strength)

(b) Artifact - function relationships (e.g., Prescribed mix - structural concrete)

(c) Heuristics (e.g., For 1" increase in slump, increase water content by 10 lb. / cu. yd.)

(d) Manufacturers instructions (e.g., Dosage rates for admixtures)

(e) Component - property relationships (e.g., Aggregate grading - water requirement)

(f) Empirical relationships (e.g., Abrams' Law[1])

(g) Microstructure - property relationships

The various relationships could be classified under three different groups depending on the level of granularity with which the property or function is associated. They are (in decreasing order of level of granularity, i.e., coarse to fine) artifact level, component level, and microstructure level.

Items (a) and (b) above are at the artifact level; that is, they represent relationships between the complete design description taken as a whole and its performance. Such relationships do not consider component behaviors or how artifact behavior is related to component behaviors. The relationships are at a coarse level of granularity and the knowledge is shallow. Volumetric mix design descriptions and concrete mix design databases of firms in the industry are founded on this category of knowledge.

Items (c) to (f) are at the component level, that is, they represent relationships between the characteristics of the primitive elements (e.g. maximum aggregate size) and properties of the mix or derived parameters (e.g. water-cement ratio) and properties of the mix. The relationships are at a finer level of granularity than the artifact level and the knowledge is deeper. Mix design descriptions developed using the standard, modern methods of mix design like the ACI 211.1-89 method or the British method, expert systems like EXMIX [Akhras 94] and the mix design method to be developed in this effort use component level knowledge.

Item (g) is at the microstructure level and represents relationships between the microstructure (microcracks, material particles, micropores, their orientations and spatial inter-relationships) and properties of the mix. The great strides made in materials research has been largely due to the study and understanding of the microstructure of materials [5]. Unfortunately, this area of research in the field of concrete technology is still in its infancy and there is not enough known about the influence of the microstructure of concrete on its properties [Mehta 86]. So far there does not appear to be any study conducted that utilizes the knowledge of the microstructure of concrete for performing mix design.

6.5.3. Design Approach

Compared to the other approaches, the design by trial mixtures approach is the least efficient approach. The ACI 211.1 and the Building Research Establishment's (U.K.) mix design methods are examples of design using trial mixtures. The expert system developed at the Royal Military College, Ontario, Canada (EXMIX) [Akhras 94]

[1] Abrams' law states that there is an inverse relationship between the compressive strength and water-cement ratio of a concrete mix.

and that developed at Clemson University [Bai 94] are based on this approach to mix design. Both these systems are rule-based expert systems and mark the first significant efforts in the application of the techniques of artificial intelligence to proportion concrete mixes [Bai 94, Akhras 94]. These expert systems for the most part follow ACI 211.1-89 guidelines. This has resulted in generic guidelines being translated into rules with the same disadvantages being transferred over to the computer-based system — that of having to perform a number of trial mixes before coming up with the final design.

Another related effort is the development of a prototype expert system called DURCON which was developed for selecting materials for the manufacture of durable concrete [Campbell-Allen 91]. DURCON's knowledge-base contains information for freeze-thaw, sulfate, alkali-aggregate and corrosion aspects of durability and is based on ACI 201 - Guide to Concrete Durability. This system limits itself to selection of materials on the basis of user-supplied information regarding exposure conditions and does not possess the capability to come up with concrete mix design descriptions.

In design-by-selection, past mix design descriptions are stored in a database or as consensus knowledge along with the conditions in which they were used and the performance of the mix made using the design. When the job conditions and performance specifications are entered into the system in the form of a query, the system retrieves one or more records that satisfy the job conditions and performance specifications. Design-by-selection uses knowledge at the artifact level. This is a very efficient approach, as long as the job conditions and performance requirements for the new concrete job are identical with some design description stored in the database. Ready-mix concrete firms like Graniterock routinely use this approach. The design-by-selection approach has helped alleviate the problems with the trial mixtures approach to a certain extent but the drawback with this approach is that we cannot obtain mix design descriptions corresponding to performance requirements and / or job conditions that are different from those stored in the database. Proportioning of standard mixes (prescribed mixes) could also be considered as examples of design-by-selection.

The approach that will be adopted in this effort is one of retrieve-and-adapt. It retrieves past mix designs from a database of cases just as in the design-by-selection approach except that it does not rely solely on exact matches (between the job conditions, performance requirements and available materials of the current design and one or more of stored designs) but allows for close partial matches. If there is an exact match, then it becomes a simple case of design-by-selection, but if there is only a close partial match, then the retrieved design description is adapted to suit current requirements. Thus, the approach of the current effort to concrete mix design could be considered as consisting of two sub-processes — a retrieve sub-process followed by either the direct use of the retrieved mix design in the event of a totally successful retrieval (i.e., a retrieval based on an exact match), or a redesign based on the differences between the retrieved mix design and the current situation. Comparatively, this approach is almost as efficient as the design-by-selection approach. At the same time it possesses the capability to arrive at new design descriptions even if exact matches are not obtained. The drawback with this approach, however, is that its performance will degrade if it does not find *close* partial matches or more specifically if the retrieved design is not close enough for adaptation to provide a meaningful solution. The term "close" implies that the differences between the current mix design problem and the retrieved design description selected for adaptation is covered by knowledge used for adaptation. This may not always be the case. However, the problem can be offset to a large extent by ensuring that, as far as possible, the database is seeded with a carefully selected initial set of prior mix design cases after the knowledge available for adaptation is formulated. In the event that a sufficiently close match is not found, the retrieved mix design description can be used before or after adaptation as a starting point for arriving at the final mix design case by making trial mixes.

At a conceptual level the retrieve-and-adapt approach closely parallels design using prototypes as explained in [Gero 90]. Gero *et. al.* define a prototype as "a generalization of groupings of elements in a design domain which provides the basis for the commencement of the design" [Gero 88]. In design using prototypes, functional requirements specified by the client are "used to retrieve potentially useful design prototypes on the basis that they are indexed by these requirements. These retrieved design prototypes represent the set of concepts that a designer remembers when s/he examines the requirements. . . . . design prototypes provide a means by which given a little situational information, potentially appropriate concepts are retrieved, and the designer has available a fleshed-out set of concepts . . . " [Gero 90]. In the approach adopted by the current effort, instead of using generalizations of groupings of elements as the starting point of the design, we use a unique grouping of elements or the most relevant mix design description as the basis from which a new design description suited to the current situation is derived.

In Figure 6.1, the point of departure is represented along the three dimensions common to other work related to this effort: design approach, workability and knowledge level. These dimensions have been explained earlier in this section. As shown in the figure, methods like the ACI 211.1 and the expert system applications EXMIX and the Clemson University system use component-level knowledge, use both intrinsic and extrinsic representations of workability, and use the trial mixtures approach for mix design. Similarly, mix design databases use knowledge at the artifact level, use the design-by-selection approach, and use both intrinsic and extrinsic representations of workability. The current effort uses knowledge at the component level, uses a retrieve-and-adapt approach, and uses both intrinsic and extrinsic representations of workability.

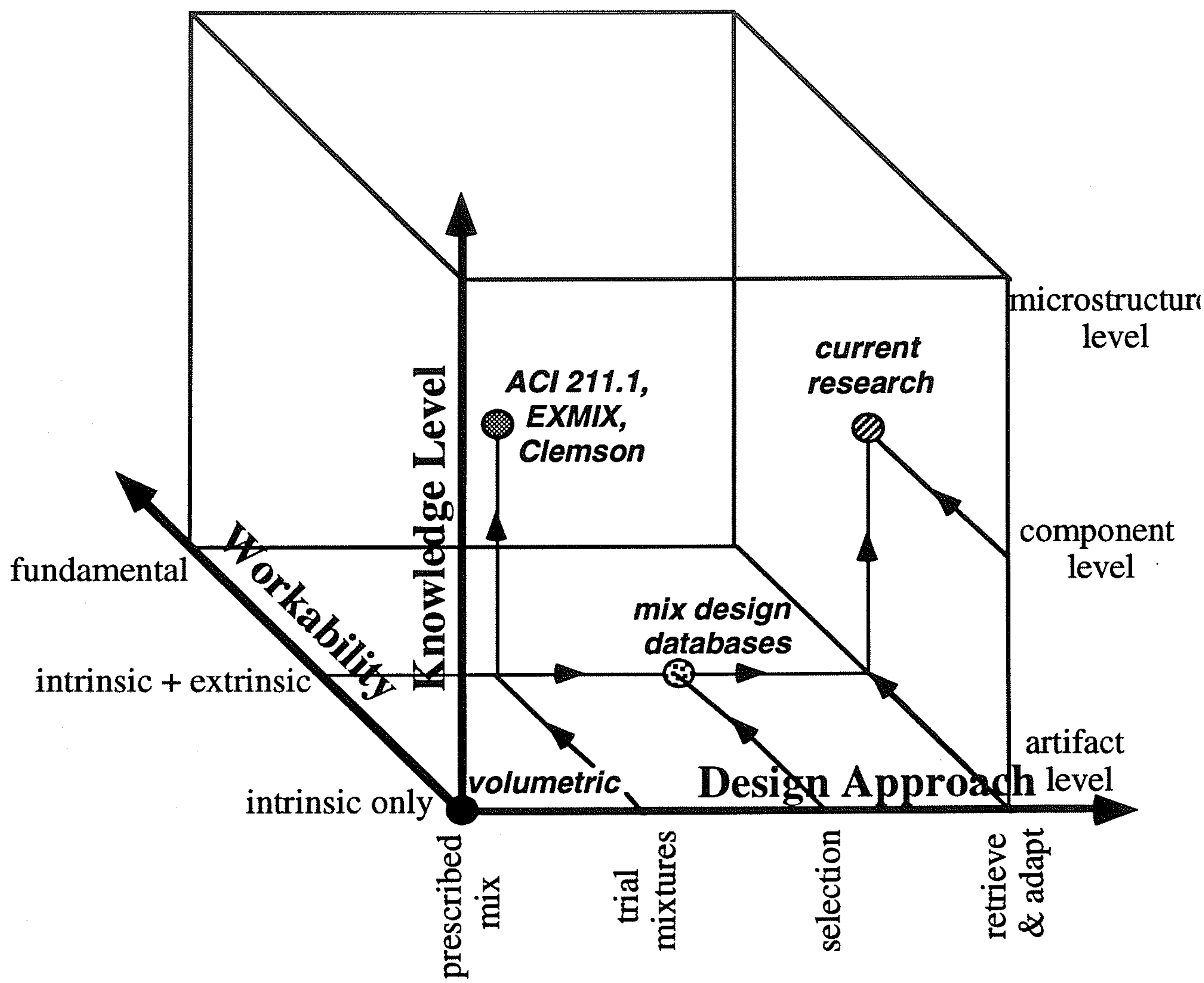

Figure 6.1. The figure shows the point of departure along three dimensions: design approach, workability and knowledge level.

6.6. Impact of Case-Based Design Methodology on Concrete Technology

The expected impact of the prototype development activity on concrete technology will be fourfold. Firstly, through an analysis of the concrete mix design process, it will provide the evidence required to alter thinking within the concrete technology community to redirect research efforts towards discovering interpretive knowledge relevant to concrete mix design for use in the development of knowledge-based systems. This could be either at the microstructural level (by providing links between performance of the concrete and the design description through the microstructure), or at the macrostructural level (between performance of the concrete and the design description).

Secondly, in the absence of knowledge required for building expert systems with the ability to simulate trials, this work introduces the idea of the development of knowledge-based design systems which circumvent the problem of insufficient interpretive knowledge by borrowing techniques used in other domains. The use of the retrieve-and-adapt technique borrowed from the field of case-based reasoning in this research is an example. More specifically, it will pave the way for the development of similar approaches to design in domains characterized by the lack of sufficient interpretive knowledge in the domain. For instance, future research can focus on the development of knowledge-based design systems for high-performance concrete mixes using the methodology developed in this research.

Thirdly, it will provide added impetus to ongoing research [Popovics 90] in concrete technology to increase the accuracy of the currently available phenomenological models (through more accurate representations of relationships between mix design parameters, use of additional parameters, etc.) and to future work related to the development of new knowledge for use in case-adaptation in more refined versions of the prototype CBR-based mix design system being developed in this research.

Finally, it will provide the concrete industry with a methodology for the development of knowledge-based mix design systems that improve upon the design-by-selection approach and also function within the limitations imposed by the knowledge-related deficiencies in concrete mix design. It will also facilitate a reduction in the number of trials required to arrive at the final mix design.

7

Conclusions, Contributions And Future Work

Although it has been widely recognized that transferring construction experience from past projects to current and future projects leads to the achievement of lower costs, higher quality, smaller project durations and better safety records, to the best of the author's knowledge, there have been no previous attempts which have researched the two important issues involved in such transfer, namely retrieval of the information most relevant to the situation at hand and the effective presentation of the information to the user which would facilitate assimilation and utilization of the information for day-to-day problem-solving. This thesis presents an attempt to develop a viable approach to solving the experience transfer problem. It discusses the use of CBR and hypermedia to address the accuracy of retrieval and utilization issues of the experience transfer problem. This chapter presents a summarization of the main points of this thesis followed by suggestions for future work.

7.1. Conclusions

This section lists and briefly discusses the important findings of this research in terms of the capture, storage, retrieval and utilization of experiential knowledge available in construction projects. The findings are as follows:

(a) High levels of commitment are required from construction organizations to achieve successful experience transfer

Due to the dynamic nature of construction, there is always a steady outflow of construction experience from projects. While there will also be an inflow, it may not match the outflow in one or more of discipline, quality and phase. In order to prevent the permanent loss of such experience, construction firms must be firmly committed to the idea of transferring construction experience. This includes making a conscious effort to recognize, capture and store such experience when the construction activity that is the source of the experience is being executed.

(b) The physical capture of construction experience poses significant problems

Given the relatively harsh environments in which most construction projects are executed, the physical capture of construction experience in multimedia format could be cumbersome, time-consuming and expensive. Furthermore, it may be economically justifiable only on large projects and may require a dedicated experience transfer team consisting of company personnel with sufficient experience in multimedia work, construction engineering and construction management. The recognition of the usefulness of a certain piece of information in some future context calls for mature judgment on the part of this team.

(c) Compared to total automation, decision-aiding would be a better strategy for the transfer and utilization of construction experience

Given the highly unstructured nature of construction projects, the brittleness of production rule-based expert systems and the constraints imposed by closed world assumptions, decision-aiding seems to be a more sensible strategy than total automation. Furthermore, the human user can bring to bear his own experience, intuition and insights in addition to the knowledge stored in the experience transfer system to tackle problems. Current computer-based systems are significantly inferior to humans in reasoning capabilities, especially at or near the commonsense end of the reasoning spectrum.

(d) Case-based reasoning and hypermedia offer powerful platforms for the capture, storage, transfer and utilization of construction experience

The case-based reasoning paradigm is naturally suited to the development of experience transfer systems because it is based on the use of prior experience stored in the form of cases. Case-based reasoning provides a great deal of flexibility in the choice of the degree of automation in the system being developed. Used in its most passive role, CBR provides an effective tool for retrieving the most relevant cases from memory and rank-ordering the cases before presenting them to the user. In its active role, it can function as a fully automated system by adapting retrieved cases to suit the requirements of the current situation.

Hypermedia provides the means to capture and store information in a number of different formats. Its sensory-rich presentation capabilities can help convey a large volume of information down to the minutest detail in a very effective manner. Furthermore, it inherits the "tirelessness attribute" of computer-based systems and is never overcome by boredom or frustration if a user requests a particular piece of information to be replayed over and over again. This allows even the difficult parts of the information to be understood and assimilated by the user in a non-intimidating environment.

7.2. Contributions

Although this research was not carried through to its culmination, it has some important contributions to make to knowledge in the field of construction experience transfer. The contributions are as follows:

(a) Identification of case-based reasoning and hypermedia technologies as software platforms for transferring construction experience

Case-based reasoning and hypermedia software platforms provide two of the most important capabilities required by an experience transfer system: (1) the ability to accurately retrieve information most relevant to the situation at hand, and (2) the ability to present the retrieved information in a manner that would facilitate its assimilation in the most effective way possible. Furthermore, case-based reasoning has the capacity to fully or partially adapt cases to suit the current requirements, thereby providing the user with additional information on which to base decisions.

(b) Development of a conceptual configuration of a mechanism for the transfer of construction experience

The mechanism utilizes the synergy developed as a result of the positive interaction amongst the CBR, hypermedia and human components of a computer-based system for the transfer of construction experience from past projects to current and future projects. The goal of such a system is to assist project personnel in problem-solving and can be designed to function in both active and passive problem-solving modes.

(c) Development of a system architecture for the hybrid computer-based decision-aiding system

The architecture is developed around a case-based reasoning shell and a hypermedia shell linked together through a Graphical User Interface (GUI). The GUI acts as a hub to which a number of modules representing various media can be connected. This ensures modularity of the architecture and the added flexibility will be useful if there is a need to either remove or add new media. The GUI is linked to the CBR shell through an Application Program Interface (API). The user interacts with the system through the GUI.

(d) Epistemological analysis of concrete mix design

As part of the process of development of a case-based system for the design of concrete mixes, the research investigated the characteristics of mix design in a search for the reasons for the lack of a strong theory underlying the concrete mix design process. More specifically, it investigated the reasons for the lack of simulation capabilities in the domain. This is significant because the ability to arrive at performance or behavior from a design description is critical to the evaluation of a potential mix design description. Most knowledge-based systems depend on such design-description-to-performance mappings being available in the domain in which they are to be developed. The understanding of the knowledge-related characteristics of the mix design domain gained in this work has provided valuable information which will be used to formulate strategies for overcoming deficiencies in the domain.

7.3. Future work

This work has revealed a number of areas where further research can yield potential contributions to knowledge. This is not a comprehensive list, but serves a start.

(a) Implementation of case-based system to design concrete mixes

The two major tasks that have to accomplished for implementing the system are: (a) solving the indexing problem in the concrete mix design domain, and (b) identifying and formalizing adaptation knowledge.

The first major issue is how do we ensure that the most appropriate mix designs are retrieved? In the terminology of CBR this is called the *indexing problem* [Kolodner 93, p. 193]. Solving the indexing problem entails assigning labels to the mix design cases as they are entered into the library of mix designs and organizing the cases (i.e., mix design descriptions and their contexts) so that the search through the library can be efficient.

The second major issue concerns adaptation of the retrieved mix designs to suit current requirements. Retrieved mix design cases, in the absence of an exact match, provide only a ballpark solution. How do we arrive at the final mix design description from this ballpark solution? Using the retrieved design as a starting point, we arrive at the final design description by "fixing" the retrieved design to suit current requirements.

(b) Physical capture of construction experience

In the area of construction experience transfer, the physical capture of construction experience appears to be one of the most difficult issues that needs to be addressed through further research. While the capture of information in multimedia format is in itself a formidable task in the harsh conditions of a construction site, there are some important questions that need to be answered even before such capture can take place: (1) Can a protocol be developed that will help experience transfer cells collect information as efficiently as possible? (2) What organizational mechanism should be in place for filtering the information before it is input into the experience transfer system? (3) Since incidents and unplanned activities (activities reacting to unanticipated changes in the state of a construction project) worth recording can occur at any point in time and at any location on a given construction project, what organizational and technological systems would facilitate the presence of the experience transfer team at the right place and at the right time? Addressing these questions has practical implications because the answers will pave the way for acceptance of computer-based experience transfer systems by firms in the construction industry.

(c) Integrating a virtual reality module to the experience transfer system

Virtual Reality (VR) technology could be used allow the decision maker to interact with a virtual construction site where he or she can experience first-hand the consequences of his or her decisions. Stereoscopic sensors fitted with position sensors linked to a computer lets the system know in real time the position of the sensor in relation to the software model of the project site or any required part of it. The system then generates two images (one for each eye) of the view of the site from the decision maker's location. By means of position-sensing gloves, the user can take hold of virtual objects and manipulate them as required. Advanced VR systems can even provide force feedback so that the objects being manipulated have weight and inertia.

7.4. Closure

This research has been an enlightening experience for the author and it is hoped that it has provided some insights into the salient characteristics of the experience transfer problem and the role that modern technology could play in facilitating the transfer and utilization of construction experience.

This research used a systematic study of the characteristics of the experience transfer problem and the requirements of a computer-based experience transfer system to select suitable technologies and to develop conceptual and software configurations for developing the system. The current work, executed under the auspices of the Center for Integrated Facilities Engineering (CIFE), will end with the establishment of a point of departure and the development of a foundation for future work involving the development of a case-based system for the design of concrete mixes using prior mix designs. The future work will be carried out as part of the author's doctoral dissertation research.

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