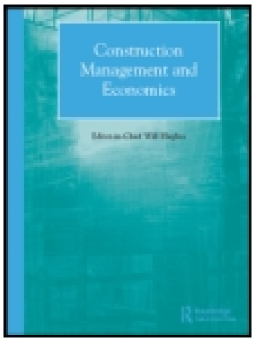

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Developing a theory of construction problem solving

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Construction problem solving characterizes much of construction management practice and thus is an important research domain. Nonetheless, research in construction problem solving has not yet crossed the threshold into a mature discipline as there is no universally accepted theory for construction problem solving research. In exploring the possibility of establishing such a theory, this paper reviews existing research works in two important research categories: cognitive science and decision support systems. A strategy for building a theory for construction problem solving, focusing on the existing models and techniques developed in the two research categories, is proposed. Future research needs and opportunities are identified.

Keywords: Problem solving, cognitivism, information processing, decision support systems

Introduction

As a subset of management science, managerial problem solving has been researched extensively from a number of perspectives (Allison, 1971; Berger *et al.*, 1986; Smith, 1992). In order to establish a theory, managerial problem solving has studied both problems and problem solvers, the nature of the managerial task and also the capacities of individuals. Existing research in managerial problem solving can be classified into two categories. The first category relates to cognitive science, in which managerial problem solving is treated as an exploration of cognitive performances of decision makers (Cronbach, 1957; Bartee, 1973; Cummins, 1983; Dyer, 1983). Research in this category is concerned with the mental activities that people employ during problem solving. The second category focuses on the techniques and strategies needed in solving managerial problems (Braybrooke and Lindblom, 1970; Simon 1978; Clancey, 1985). This category encompasses a large volume of research progressing the task of problem solving from building decision trees, through decomposing tasks into predictive and evaluative judgments, to using intelligent decision support systems.

Akin to the general trend of managerial problem solving research, many of the research activities in construction problem solving can be classified into the same two categories. However, current research in construction problem solving has been focused heavily on developing decision aids, innovative techniques and methods for construction professionals to formulate and solve problems. Very little research has been done in understanding construction problem solving as a mental process. Construction management activities are fundamentally problem solving activities and a theory for construction problem solving will provide a vehicle by which the research area can develop and progress (Runeson, 1994). Without such a theory, we will stay at the information collection stage, repeating similar exercises with slight variations. The purpose of this paper is to explore the possibility of inducing a theory for research in construction problem solving by connecting various models developed in problem solving research. Specifically, the paper examines characteristics of construction problems and problem solving, highlighting the difficulties in establishing a theory for construction problem solving research. Relevant research in management science is critically reviewed, with a view to evaluating its suitability in construction applications. Research needs and opportunities are then defined after discussions on contributions and limitations of current research. It is expected that this paper will provide a starting point for progressive research in the development of a theory for construction problem solving.

Construction problems and problem solving

The construction industry necessarily comprises various parties, each having their own perceptions and objectives. Problems are transpired as entities involving a relationship of dissonance between construction situations and preferences. A theory of construction problem solving must consider the nature of construction problems, the problem solvers, as well as the construction industry within which problems transpire and individuals seek solutions.

The ill-structured nature of construction problems

Construction problems are notoriously ill-structured: there are so many uncertainties (variables) and variations in a construction problem, making it difficult, if not impossible, to identify a finite set of variables to describe a given problem. A comparison of construction problems with problems in structural engineering, our neighbouring discipline, may help us clarify the weakness. In structural engineering, there exists a finite set of variables, e.g. stress, strain, bending moment, etc., and these variables are universally recognized and accepted within the discipline. When a problem arises in structural engineering, these variables are sufficient to represent the knowns and unknowns. Therefore efforts are focused on exploring the unknowns. However, research in construction problem solving cannot enjoy such a convenience. In most construction problems, identifying appropriate variables forms a substantial part of the research effort. Typical examples may be those research activities in stimulating bidding behaviour. Researchers have to determine what are the most important factors (variables) that influence bidding decisions. Different researchers may propose different sets of variables according to different social, economic and environmental backgrounds (Skitmore, 1989; Smith, 1995).

Even if there is a finite set of variables, construction problems are still ill-structured. The next difficulty is the lack of understanding of the interrelationships between variables. In structural engineering, the functional relations between variables are well studied. For example, the relation between stress and strain is well established and proven. There exists a body of proven axioms and conceptual models that can be used to evaluate new research results. In contrast, relations between variables in construction problems often are not well understood. If we still use bidding research as an example, although there have been many efforts to identify the quantitative relationships between bidding variables, little has been conceptualized and accepted by the research community and the industry as a whole. Because of this, experiential knowledge has an important role to play in construction problem solving.

The third aspect of the ill-structured nature is characterized by the fact that construction problems possess multiple solutions. Construction tasks always have several objectives to strive for, such as minimizing time and cost, and maximizing quality. Even if some objectives can be optimized, many others rarely achieve optimality. Therefore, in a real construction situation, the effort to optimize shifts, and is replaced by the need to sacrifice or compromise. As a direct consequence, solutions to a construction problem are always multiple.

Construction problem solving

Problem solving requires representing the problem in a language that problem solvers can understand and reason about. While it is difficult to conceptualize and define construction problems with variables uniformly accepted in the industry, different construction problem solvers perceive construction problems from different perspectives, and develop the interpretations and representational structures (schemes) with emphasis on different aspects. This suggests that several schemes may be applicable to a single construction situation. However, the representational schemes employed by problem solvers are poorly understood and inadequately studied.

Because there is not an adequate vocabulary (set of variables) in the domain of construction problem solving, communications between practitioners and researchers become a real problem. Practitioners feel they know more than they can describe; researchers offer little help because there is a lack of theoretical constructs to explain types of construction behaviour.

Another characteristic of construction problem solving is its reliance on experiential (empirical) knowledge. Experiential knowledge is not codified in books and is weakly organized in memory (Li, 1994). As long as problem solvers perceive construction problems with different perspectives, the body of experiential knowledge may appear to be diverse or even disparate. As a result, knowledge evocation becomes difficult and fallible. On the other hand, because there is little generalization and conceptualization from the experiential knowledge, problem solvers often (mistakenly) adopt the first plausible solution they construct, with no formal means to further improve and elaborate the solution.

Moreover, construction problem solving often lacks clear procedural structure. Often, the next step of problem solvers is heavily conditioned by the outcome of previous actions (Weick, 1983). This is partially because of the absence of formal knowledge, and partially because of the one-off nature of construction problems. The uniqueness of construction problems immunizes them against proceduralization. Although many construction tasks are preceduralized, construction problem solving tasks are simply those that cannot be structured in the same way.

The construction industry

The construction industry is heterogeneous in the nature of its organizations. In order to procure a construction project, various organizations are combined for a while to create a 'temporary multi-organization' (TMO) (Cherns and Bryant, 1984) to discuss and exchange information. When construction problems arise, relevant organizations have to work together to determine appropriate concessions and compromises before solutions can be obtained (Alty, 1993). Thus construction problem solving activities occur at both organizational and individual levels.

The construction industry is centred around projects in which organizations come to work together within the durations of the projects. Each project is unique in the sense that there are 'properties' of construction problems that are inseparable from the project. In solving construction problems, a great deal of solvers' efforts are directed at understanding the problems in order to recognize the similarities of the problems at hand with previous solved problems. The similarities will enable solvers to recall their experiential knowledge: there is insufficient formal and procedural knowledge to solve construction problems, so construction problem solvers have to rely on their experiential knowledge.

Existing research in problem solving

As stated previously, research in problem solving has been focused on two major categories: cognitive processing and development of problem solving strategies. This section reviews existing research works in both categories.

Cognitive processing models

The purpose of cognitive research is to develop models to explain cognitive phenomena occurring during problem solving. In this research, the problem solver is assumed to be able to translate the description of a problem into some internal cognitive representation. This translation involves mentally encoding the given state, goal state, and legal operators for a problem (Myer, 1983). Once the problem is represented internally, the internal mental system responds by selecting a particular problem solving method. The solution involves filling the gap between the given and goal states. In other words, a solution involves devising and carrying out a plan for operating on the representation of the problem.

For all the cognitive models developed, Simon's (1965) intelligence-design-choice model is perhaps the most important. In this model, cognitive reasoning is depicted as a rational process involving recursive generation and interpretation. Cowan's (1986) model of problem recognition shows the degree to which problem descriptions can be re-defined. Newell and Simon's (1972) generate-and-test model argues that problem solving can be modelled by a recursive process of generating potential solutions and then testing the solutions. Lang *et al.* (1978) provide a comprehensive review of the developments in cognitive modelling. A recent account is provided by Carlson (1997).

As a side area of cognitive science, research has been conducted on the essential types of skill that problem solvers need in order to achieve their objectives. Katz (1974) considered that there are three types. The first type of skill embodies some formal education and training which enables the recipient to develop a competent level of professional knowledge. The second refers to the ability to work with other people in problem solving activities. The third comprises abilities to perceive problems from different views and to provide solutions for the benefit of the whole rather than a small part of an organization's objectives.

Although cognitivists claim that cognitive modelling provides a useful account for general problem solving activities (Berger *et al.*, 1986), its impact on construction problem solving practice and research remains to be seen. On the other hand, researchers advocating problem solving as information processing have argued that findings in cognitive modelling are weak and inconclusive. The major criticisms concern the relatively arbitrary choices among the many natural language terms in describing the anatomy of mind. Rather than establishing an authoritative lexicon of cognitive science, cognitive researchers describe thought with a loose network of concepts derived from the terms of everyday affairs. Many of these concepts are poorly defined, and important relationships have not been specific (Stich, 1983). Another limitation is the existence of mental 'black boxes': attempts to represent mental process with smaller components run into seemly inexplicable capacities that have to be treated as black boxes. Therefore, further research is needed to clarify the confusion caused by the lack of a scientific lexicon and to explain some prescriptive abilities of human cognition.

Problem solving as information processing: decision support systems

Problem solving as information processing is an important and well-researched area. In its simplest term, this research area views a problem solving task as involving formulating an explicit statement of goals for the problem to be solved, identifying the scope and boundaries of the space of feasible solutions, and selecting the optimal solution between a set of alternatives. It is assumed that a problem presents an unsatisfactory situation where conflicting properties and objectives coexist. It is necessary to establish the interrelationships between the properties before a realm of feasible solutions (or solution space) is defined. The solution space is typically multidimensional, and the axes have different scales and units of measurement. Once defined in this fashion the problem becomes the selection of an optimal solution within the area delineated, i.e. a solution which lies in the space and is better, according to some measure of utility, than any other feasible solutions.

Information processing researchers have been concentrating primarily on investigating the step-by-step performance of problem solving in order to develop decision support systems (DSS) to assist problem solvers. Fundamentally, decision support systems are systems designed to support decision makers. There are two basic approaches to developing decision support systems: operations research (OR) and artificial intelligence (AI).

OR based DSSs utilize mathematical methods to solve problems, and OR techniques can be used to abstract a problem into relationships and construct a model of reality. The specification of relationships within the model is usually represented mathematically. Solutions to the problem are generated by the model, and the best or optimal solution is presented. In general, an OR based DSS has to have a component which takes in criteria and conditions of a decision problem to formulate a decision model, a component to generate alternative solutions from the model, and a component to evaluate the alternative to identify the optimal solution. Normally, OR based DSSs are used to solve well structured decision problems in which, mostly, decision variables can be quantified (Thierauf, 1982).

The focus of AI research is on the design of systems that can solve problems traditionally considered to be solvable only by intelligent humans. The most prominent area in AI is expert systems, which ties together much of the research in the field. An expert system (ES) provides feasible solutions to decision problems in a particular problem domain. This is achieved by articulating and storing relevant knowledge about the problem domain in the ES system, along with general models of how the knowledge should be utilized. Knowledge used in an ES includes human expertise, heuristics, facts, and rules about a problem domain. Decision making processes in expert systems often are modelled after the cognitive processes by which decision makers arrive at their decisions. AI based DSSs are in fact expert systems that aim at supporting decision makers just as OR based DSSs do. AI based DSSs are used to support decision processes in which qualitative as well as quantitative aspects in a problem play an important role. They can be applied to solve semi- and ill-structured problems.

There exists a large volume of research in the development of a DSS for general problem solving purposes, and a comprehensive review can be found in McLean and Sol (1986). Attention is now directed at construction related DSS research. Research in construction problem solving models has been shaped largely by the advances in information technology (IT). In recent years, many IT based DSSs have been developed to support construction problem solvers in information-gathering, identifying available alternative solutions, and selecting the optimal solution. Examples of OR based construction DSSs are: Skibniewski and Armijos (1990), who developed a DSS which applied linear programming (LP) to assist construction labour and equipment allocation decision making problems; Burns *et al.* (1996), who developed an integer programming based DSS to support construction time–cost optimization problems; and Attwood (1989), who developed a DSS using decision trees in human resource management problems.

During last decade, AI based DSSs (or expert systems) have been developed to support decision making and problem solving processes in the construction industry, e.g. Watson *et al.* (1991) and Brandon (1992), who reported three expert systems, ELSIE, ELI and EMMY which have been developed for use in the strategic planning of construction project; and CONSAS, which is an expert system for construction scheduling analysis, was developed by Ibbs and Garza (1988) to demonstrate the usefulness of expert systems in the construction industry. An expert system has been developed by Mathur and Leng (1992) for building defect diagnosis. Also there are expert systems for dispute resolution (Diekmann and Kuppenbacher, 1984; Al-Shawi and Hope, 1989) and for the interpretation of construction law (Betts *et al.*, 1994). A comprehensive review of using AI-based DSSs in the construction industry is presented in Levitt (1987).

Towards a theory of construction problem solving: direction for future research

Both of the cognitive processing and information processing approaches have led to models that add to our understanding of construction problem solving. It is proposed, however, that these two research streams, as currently conceived, cannot individually provide a theory for construction problem solving. A theory attempts to explain observed phenomena and predict types of behaviour that are somehow connected. Models are less ambitious than theories. Models can only explain and predict a subset of phenomena and behaviour. Hence there is a wave model of the behaviour of light and there is a particle model. Neither model on its own, gives a wholly satisfactory explanation of the behaviour of light, and the two are now subsumed under the theory of quantum mechanics.

Therefore it is proposed that a theory of construction problem solving should be built upon models developed in the two research streams: cognitivism and DSS research (Figure 1). Cognitivism may help explain human behaviour in construction problem solving. DSS researchers can provide a rational basis for investigating the step-by-step performance of problem solving activities. In order to develop a theory for construction problem solving, it is necessary to examine the important research issues that need to be investigated in both research streams.

Future research issues in cognitive processing

Although construction problem solving can be categorized as a subset of general problem solving and most knowledge of cognitive science is relevant to construction problem solving research, a limited set of mental process models should be distilled from the existing body of cognitive science to meet the purpose of theorizing construction problem solving research. Concepts and terms must be defined through the analysis of critical construction problem solving cases. The terms should be employed more carefully, consistent with their definitions in construction.

As stated previously, the absence of scientific knowledge in explaining the overall process of human problem solving results in many black box elements in cognitive science. In construction problem solving tasks, individuals or collectives are faced with unsatisfactory construction situations and are motivated to change them. Thus motivation is transparent. Much at stake are the internal representations individual problem solvers developed from the way they perceive the construction problems. Much research is needed in order to arrive at a scientific understanding of the mental representation employed by construction problem solvers.

Because there is a lack of formative and procedural knowledge to derive solutions, construction problem solvers need to generate and apply common-sense, experiential knowledge to determine a course of action. The activation of such knowledge is motivated by the reasoning towards achieving the goal states. Of the problem solving strategies that might be employed, most depend for their effectiveness on the problem solver's evocation of experiential knowledge. However, central questions yet to be addressed are: how do construction problem solvers accumulate experiential knowledge from construction practices?; and what are the mechanisms underlying the transition from novice to expert? Understanding human learning is one of the central problems in cognitive studies, and it opens another research opportunity for establishing a theory for construction problem solving.

Another concern is the influence of personal traits on the outcome of construction problem solving tasks. It has been suggested that genetic differences influence behaviour in more ways than often is assumed (Arvey *et al.*, 1989). Although some of the individual difference research has been controversial, it may be worthwhile to screen the claims made by such a research area and be alert to the potential existence and importance of personality factors in construction problem solving.

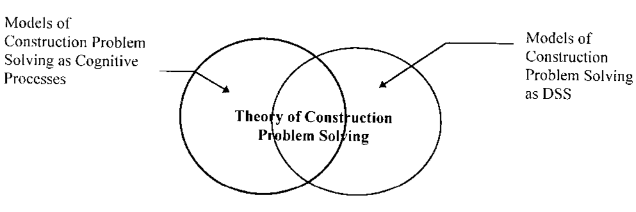

Figure 1. Theoretical basis of construction problem solving research

Future research issues in DSS

As the most fully developed stream, DSS encompasses a large volume of research. However, in order to distill a limited number of conceptual models, this research stream requires more disciplined conceptualization in the definition of construction problem representation, reasoning and acquisition of construction knowledge. A problem representation of construction is a medium that facilitate the communication between construction reality and reasoning activities that lead to problem solutions. The importance of problem representation, and the fact that construction problems are ill-structured and defined, create a research opportunity. The need for a problem representation generally is recognized in the development of construction DSSs.

However, there are two major concerns in seeking an appropriate representation. The first concern grows out of the fact that a representation is an abstraction of a particular phenomenon. If one wants a DSS to simulate some kinds of construction problem solving capacity, then which is the appropriate level of abstraction for construction situations? Another concern, which generates some other research opportunities, bases itself on a rather theoretical view, and points to the structure of the representation. This concern goes something like this: construction problem solving is an intelligent activity that eludes formal or rigid description; if a representation has a role to play, then to what degree is flexibility required so that a problem representation can facilitate a broad spectrum of reasoning and searching paradigms? Further research is needed urgently to clarify these two concerns.

The continuous search for new construction problem solving strategies and techniques has long received a great deal of attention from construction DSS researchers. However, researchers must specify and characterize the strategies that human solvers use during their construction problem solving activities. A means of relating strategies to classes of construction problem must be identified so that appropriate strategies can be prescribed and selected for certain problems. Clancey (1985), for instance, described a classification method in which one identifies a problem as being of a certain type, and solves it by applying knowledge 'embedded' in that type.

Empirical data must be collected to determine if classic fallacies of informal logic (e.g. over-generalization) are prevalent and what other kinds of weakness occur in the reasoning about construction problems. Adequate measures are required to evaluate the performance of a DSS. This evaluation must include the representational adequacy, the plausibility of inference and the quality of the resultant solutions.

The fact that construction problem solving relies heavily on experiential knowledge needs further investigation. It may be useful to view construction problem solving as a community activity: problem solvers do not operate within a vacuum but adopt and adapt solutions and methods practised and learned in previous cases. The existence of previous problem solving cases (examples) makes machine learning research plausible. There are two major machine learning paradigms that can be applied to acquire construction experiential knowledge similarity based learning (SBL) and explanation based learning (EBL). SBL relies on a paradigm of comparing examples and analysing them in terms of similarities and differences. EBL views learning as a knowledge-intensive activity: it takes a single example, builds up an explanation of how various components relate to each other by using artificial intelligence (AI) understanding and planning methods, then generalizes the properties of various components of the example as long as the explanation remains valid. The applicability of both SBL and EBL must be investigated in the task of acquisition of experiential knowledge from construction problem solving examples.

Conclusions

This paper has examined cognitive science and DSS research as two research streams that contribute to an understanding of construction problem solving. Although existing research in cognitivism has contributed to the explanation of human behaviour in problem solving, additional research is needed to explore the impact of the uniqueness of construction problems on the behaviour of problem solvers. An authoritative lexicon of cognitive concepts and terms must be established specifically for formulating the theory of construction problem solving. In the stream of DSS research, future research directions should be extended to the identification of appropriate problem representations, adequate reasoning strategies and mechanisms for automatically acquiring experiential knowledge from past construction problem solving examples.

If one accepts Kuhn's view of the route to 'mature science' (Kuhn, 1970), then the study of construction problem solving is at the 'pre-science' phase. It has yet to receive its first universally accepted theory. According to Kuhn's view, the next phase is 'normal science' within which a theory is established to streamline and incorporate various models developed in the 'pre-science' phase. In order to prepare the entry into the next phase of progress, research in construction problem solving should be consciously directed to the research needs and opportunities identified in this paper.

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