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Inductive Learning in Civil Engineering

Enseignement inductif en génie civil

Anwendungen induktiver Systeme im Bauwesen

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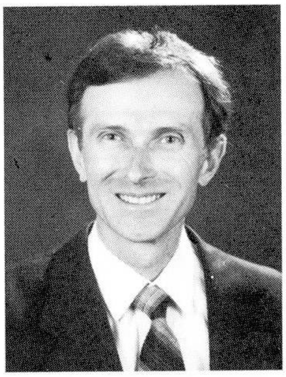

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SUMMARY
This paper discusses several potential civil engineering applications of inductive systems. An inductive system is a computer program using learning from examples to extract a system of decision rules. An inductive system can be used in knowledge acquisition for expert systems, and also for problem-solving, shallow modeling, learning about different domains, and in learning expert systems. All these potential applications are discussed and examples given. The examples were obtained using a class of experimental inductive systems based on the theory of rough sets.

RESUME
Cet article traite d'applications potentielles de systèmes inductifs en génie civil. Un système inductif est un programme d'ordinateur avec l'aide d'exemples, qui extrait un système de règles de décision. Il sert aussi comme un outil d'acquisition des connaissances pour les systèmes experts, et comme solution pour des problèmes de petits modèles, pour apprendre des domaines différents et pour enseigner les systèmes experts. Toutes les applications potentielles sont discutées, et des exemples sont présentés. Ces exemples sont obtenus pour des classes d'expériences de systèmes inductifs, basés sur la théorie des «rough sets».

ZUSAMMENFASSUNG
In diesem Beitrag werden mehrere potentielle Anwendungen induktiver Systeme in Bauwesen diskutiert. Ein induktives System ist ein Computer Programm, das von Beispielen lernt, um ein System von Entscheidungsregeln abzuleiten. Ein induktives System kann zur Wissensgewinnung für Expertensysteme, aber auch zur Lösung von Problemen, für oberflächliches Modellieren, zum Lernen in verschieden Wissensgebieten und für lernende Expertensysteme eingesetzt werden. Alle diese potentiellen Anwendungsgebiete werden mit Beispielen diskutiert, Diese Beispiele wurden mit einer Klasse von experimentellen induktiven Systemen erstellt, welche auf der «rough sets»-Theorie basieren.

1 INTRODUCTION

The civil engineering profession is in a period of intensive change, reflecting progress in various areas of science and technology. In particular, developments in computer science, especially in the area of artificial intelligence, are important for our profession. Knowledge-based systems and inductive systems are particularly useful for civil engineers. There is a large body of available civil engineering knowledge, accumulated over the centuries, which is difficult to use directly in the decision making process. This knowledge, however, can be used in decision-support computer tools, and can significantly improve the present practice of decision making in the design and management of civil engineering systems. The importance of this new area has been recognized by the American Society of Civil Engineers. In 1985 the ASCE Expert Systems Committee was established to stimulate and coordinate research and development related to expert systems technology in civil engineering [11]. This Committee also initiated the publication of a monograph series entitled "Expert Systems in Civil Engineering". The first volume [12] has already been published and others are in preparation [15]. The area of expert systems is considered in our profession to be one of the most promising, and there has been significant progress in this area, demonstrated by a number of recently published books and papers [1,2,10,13,16,18]. Expert systems have also become a part of civil engineering curricula at a number of U.S. research universities [8,15], and there is growing interest in the practical applications of expert systems.

This paper provides a brief review of potential applications of inductive systems in civil engineering, including examples of experimental applications developed at Wayne State University's Civil Engineering Department, Intelligent Computers Center. An inductive system is understood here as a computer program that uses learning from examples to extract a system of decision rules. From the civil engineering point of view, an inductive system can be considered as a black box, that is, as a new tool which can be used for different purposes. This new tool has significant advantages over human experts. Humans are very good at deduction, at using available general knowledge for dealing with individual problems. However, we have very limited inductive abilities. By induction, we mean the development of general knowledge from examples. Humans can handle only a very limited number of examples and attributes of a problem at the same time. Sillen [17] describes a human brain as a computer. He notes, that an average human can handle only seven attributes and seven examples at the time, while a computer can deal with a large numbers of both attributes and examples, limited only by the available working memory. This comparison clearly explains why computers are better than humans at learning from examples.

Inductive systems have already been used in space industry for the extraction of decision rules from examples to be used in an expert system [14], and for different industrial problem solving applications [17]. However, in civil engineering, applications of inductive systems still have mostly experimental character [3,5,6,19].

The approach to computer learning from examples must be different in civil engineering than in computer science. Computer scientists are interested only in the internal workings of an inductive system. As civil engineers, we want to know the potential applications of inductive systems, and we want to know how to use different inductive systems.

For these reasons, an engineering methodology of inductive learning has been developed at Wayne State University [4,7]. This methodology deals with the process of using inductive systems in knowledge acquisition, with applications for different civil engineering purposes. This work is intended to close the present gap between engineering and computer learning, and to stimulate engineering applications of inductive systems.

The engineering methodology of inductive learning is defined as a subarea of computer learning dealing with the process of inductive learning from the user's point of view. In the proposed methodology, the following three components have been distinguished: 1) inductive learning process, 2) selection of examples, 3) control criteria. Its initial outline is given, however, in [7]. This methodology was prepared for engineering applications, and should be useful for anyone interested in the practical use of inductive systems.

Our research indicates that an inductive system can be used for different civil engineering purposes. At least five possible applications of inductive systems in civil engineering have been distinguished:

1. Extraction of decision rules from examples for application in rule-driven expert systems.
2. Inductive problem solving.
3. Inductive shallow modeling.
4. Learning about a given domain through the process of gradually extracting decision rules from examples.
5. Learning expert systems for engineering applications, for example for conceptual design or for control.

These potential applications are discussed and examples of individual applications given, obtained using a class of experimental inductive systems based on the theory of rough sets and developed by Voytech Inc. of Regina, Canada.

2 EXTRACTION OF DECISION RULES FROM EXAMPLES

This application of inductive systems is the best known, and requires only a very few comments. It is well known that knowledge acquisition is a bottleneck in the development of many expert systems. Knowledge elicitation from domain experts is usually very time-consuming and requires the involvement of high-priced knowledge engineers. The process of knowledge elicitation is particularly difficult in all cases where decision rules are complex and are based on many attributes. In such cases traditional methods of knowledge acquisition are ineffective, and only very rarely are the expected results obtained on schedule and within budget.

The application of an inductive system changes this situation drastically. Very complex decision rules can be generated, involving a large number of attributes. Traditional development of such rules would be very difficult, if not impossible.

The developed methodology of inductive learning [7] can be used to guide engineers through the process of extracting decision rules from examples. This methodology is currently available, and inductive systems can be used as expert system building tools even today.

3 INDUCTIVE PROBLEM SOLVING

Inductive problem solving is defined as a process of extracting decision rules from examples to find one decision rule which is crucial to solving a problem. Its potential applications are much broader and more interesting than the simple extraction of decision rules from examples to be used in an expert system. Inductive problem solving can be considered also for immediate application, and should be particularly attractive to all civil engineers dealing with complex problems.

Very often, engineering problems cannot be solved, due to their complexity. A number of decision rules governing such a problem may be known, but there is still one rule missing. This missing rule, or as we call it, this "missing link," is crucial to the solution of the problem. The missing link cannot be found using traditional methods of analysis, because of the large number of examples, the large number of attributes, or both.

The limitations of human working memory have been mentioned in the Introduction. These limitations explain why human experts are very bad at dealing with such problems. The application of an inductive system can improve the situation immediately. All examples may be analyzed by an inductive system, and all decision rules, including our missing link, may be found immediately.

There are known engineering applications of inductive problem solving; Novacast of Sweden has a very impressive record here. For example, this company has used inductive systems for solving complex problems related to the production of margarine and the determination of its melting point. Another successful application was the determination of the factors causing cracks in welds in off-shore drilling platforms [17].

A simple problem from the area of quality control in the manufacturing of steel beams will illustrate the concept of inductive problem solving. The problem is described by several attributes, including the conclusion, which represents the quality of a steel beam. These attributes and their values are given in Table 1.

NO.	ATTRIBUTES	ATTRIBUTE VALUES		
		1	2	3
1	TYPE OF STIFFENER	STANDARD	EXPERI-MENTAL	
2	TYPES OF WELDS	FILLET	DOUBLE FILLET	GROOVE
3	WELDER'S EXPERIENCE	LOW	AVERAGE	HIGH
4	HUMIDITY	LOW	NORMAL	HIGH
5	TEMPERATURE	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE
6	PRODUCT QUALITY	GOOD	BAD	

Table 1. Manufacturing of steel beams: attributes and their values

It was noticed that in some cases the quality of the beams was bad. Unfortunately, human experts could not find the reason. An inductive system was used to analyze all available 22 examples, based on 5 attributes, and given in Table 2.

The inductive system immediately extracted a rule, which provides the solution to the problem. This rule is given below:

When:
    A1=2, stiffener is experimental,
    A3=1, welder's experience is low,
    A4=3, humidity is high,
    A5=3, temperature is high,
then:
    A6=2, the product is faulty.

This problem is relatively simple, but it shows the potential applications of inductive problem solving.

4 INDUCTIVE SHALLOW MODELING

Inductive shallow modeling is defined as a process of building a shallow model of an engineering system, physical or abstract, using an inductive tool.

Traditional or deep modeling is based on the assumption that we understand the behavior of an engineering system, and that we have its conceptual model. This conceptual model can then be used for building a formal mathematical model using available experimental results.

Very often, however, our understanding of the behavior of engineering systems is incomplete. In this case building formal mathematical models based on their predicted behavior is very subjective and simply incorrect.

Shallow modeling is based on the system's observed behavior. An understanding of the system is not required. Obviously, such modeling has significant advantages over traditional deep modeling. It is particularly useful in the modeling of very complex systems of unknown structure. Our initial experience in this area indicates that inductive shallow modeling may become very important, especially in engineering research. This experience and our initial methodological suggestions are presented in the paper [9].

To demonstrate the use of shallow modeling, the results of an inductive experiment conducted about two years ago [9] will be briefly described here.

Example No.	ATTRIBUTES					
	1	2	3	4	5	6
1	1	1	1	1	1	1
2	1	1	1	2	1	1
3	1	1	1	3	1	1
4	1	1	1	1	2	1
5	1	1	1	1	3	1
6	1	1	1	2	2	1
7	1	1	1	2	3	1
8	1	1	1	3	2	1
9	1	1	1	3	3	1
10	2	1	1	1	1	1
11	1	2	1	1	1	1
12	1	3	1	1	1	1
13	2	1	2	1	1	1
14	2	1	3	1	1	1
15	2	1	1	2	1	1
16	2	1	1	3	1	1
17	2	1	1	1	2	1
18	2	1	1	1	3	1
19	2	1	1	3	3	2
20	2	2	1	3	3	2
21	2	3	1	3	3	2
22	2	3	3	3	3	1

Table 2. Manufacturing of steel beams: examples

In the experiment, the results of only 15 tests of steel beams under bending were used. An inductive system was applied to confirm the existence of well-known relationships between different groups of variables.

In particular, we were looking for answers to the following questions:

1. Is the moment of inertia (V3) of our beams related to their depth (V1) and thickness (V2)?
2. Is the ultimate beam capacity (V6) related to its moment of inertia (V3)?
3. Is the ultimate capacity of the beam (V6) related to the measured strains (V7, V8) and calculated strains (V10)?

The modeling was conducted as a progressive learning process, and the results were recorded after each added example. These results are shown in (Fig.1).

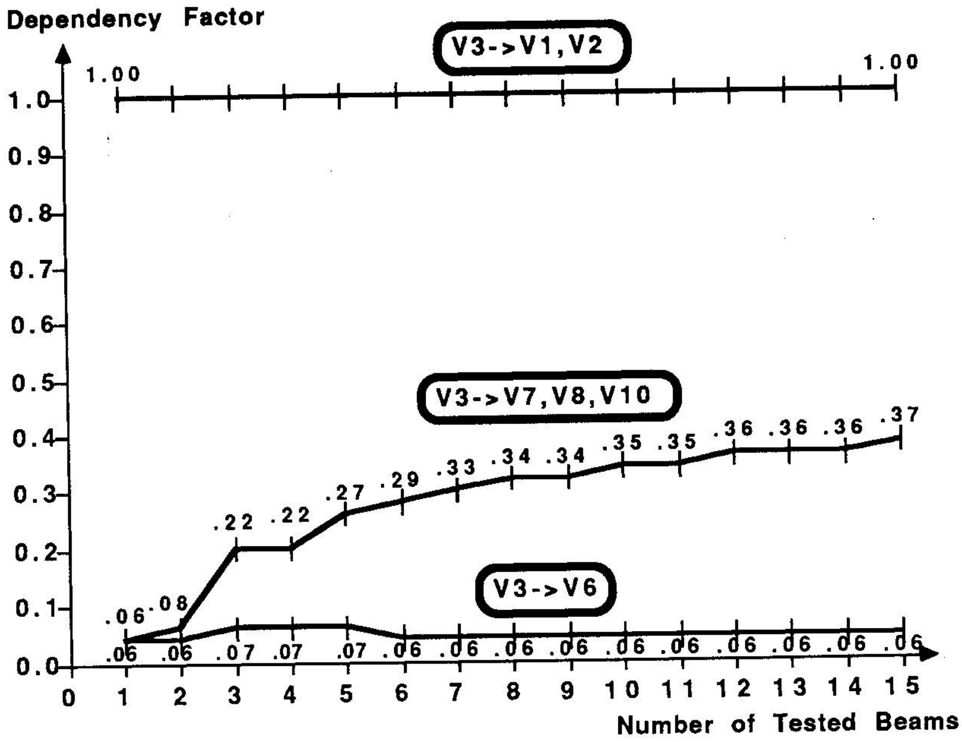

Fig. 1. **Inductive shallow modeling: learning curves [9]**

It can be easily seen that the answer to the first question is a very strong Yes.

In the theory of rough sets, the dependency factor measures the strength of the relationship between given variables and a group of variables. In this case the dependency factor equals unity, indicating a functional dependency.

The answer to the second question is more complex. There is a relationship between the moment of inertia and the ultimate capacity, but this relationship is not functional, and is relatively weak.

The results obtained for the third question indicate that the learning process has not been completed, but there is definitely at least a weak relationship.

Inductive shallow modeling is still in the experimental stage, but even now it could be useful for practical purposes, particularly in cases where traditional methods of deep modeling are not sufficient.

5 INDUCTIVE LEARNING ABOUT DOMAIN

Inductive learning about domain is defined as a systematic and monitored multi-stage learning process in which an inductive system is used as a learning tool. The objective of this process of learning is to improve the understanding of a given domain through the systematic development of a system of decision rules governing this domain.

Very often in civil engineering we have a large body of known examples. We spend months or even years on studies of a given domain, but because of its complexity we do not really understand it. We may identify several simple decision rules governing this domain, but we still need a more fundamental understanding. We simply need more fundamental decision rules governing our domain. This is a typical situation in the research and development of new engineering systems. We identify all known solutions and we want to understand all these solutions, which are our examples.

In this case we can use an inductive system as an engineering learning tool, a new tool which can be used by a human expert to learn about a complex domain. This new tool is used in a multistage learning process (Fig.2). At each stage of this process an inductive system is used to extract decision rules from a different collection of examples. The decision rules and parent examples are recorded. A human expert analyzes all examples and related decision rules, and tries to relate these decisions to examples and to improve his understanding of a given domain.

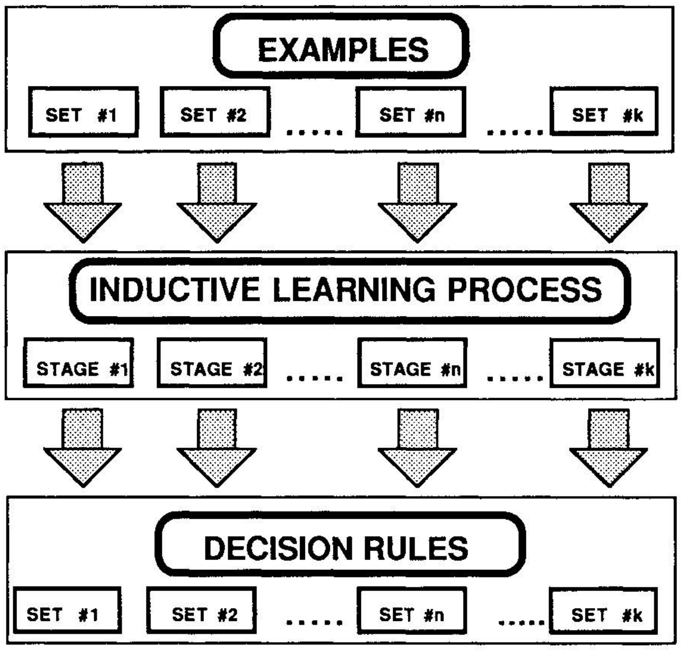

Fig. 2. **Inductive learning about domain: a multistage process**

This potential application still needs a lot of research and experiment, but it looks very promising.

6 LEARNING EXPERT SYSTEMS

A learning expert system is defined as an expert system with a learning component. Such a system has the ability to learn, (i.e.) to modify its decision rules to follow changing conditions. A learning expert system can be developed for the purposes of conceptual design, diagnosis, or control [3,5].

To explain the concept of a learning expert system, a system for conceptual parametric design will be briefly described here. [3] By "conceptual parametric design," we mean an early stage of the design process. In this stage, design needs and the available knowledge are analyzed and a number of concepts of a future civil engineering system are generated. In parametric design, a system under consideration is described by parameters and the design process is a sequence of operations on these parameters, including the identification of feasible values of these parameters and the determination of the optimal combination of parameters values. In conceptual design, the parameters considered are mostly qualitative in character, and a compatible combination of their values, when for all parameters one value is taken at a time, identifies a concept of a civil engineering system [3].

A learning expert system for conceptual design can be used for the production of concepts. These concepts can be selected from the generated combinations of values of qualitative parameters, using internally produced compatibility rules. In this case the system has to be used in two stages: learning and production. The objective of the first stage is to extract, from given examples, a system of decision rules governing a given domain represented by the examples. In the second, or production stage these decision rules are used for the evaluation of combinations of values and the selection of compatible combinations, which represent the concepts being sought. More details on learning expert systems for conceptual design and the results of structural experiments are given in [5].

In the case of conceptual design, the use of inductive learning has many advantages. It enables us to deal with a large body of examples, and also leads to the development of very complex decision rules, which otherwise would not be prepared because of their complexity and unusual character. A learning expert system for conceptual design has the ability to produce standard, well-known concepts, but there is also a possibility that it will produce innovative, patentable concepts. The present research on learning expert systems for conceptual design is still in its early stages, but its potential is enormous, and very interesting developments can be expected in the future.

7 CONCLUSIONS

Inductive learning in civil engineering is still in its early experimental stages. Available experience is very limited, but the initial results indicate that inductive systems may very soon become powerful tools in civil engineering, useful for different purposes, as proposed in this paper. It is difficult to predict, however, which civil engineering application of inductive systems will be the most important, or which will have the greatest practical impact. All potential applications of inductive systems are feasible even now, and should become of interest to both practitioners and researches.

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