NEW PARADIGMS IN SYSTEMS ENGINEERING: FROM "HARD" TO "SOFT" APPROACHES

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Abstract. Developments in fuzzy sets theory are considered in relation to those in expert systems. It is suggested that these are not just mathematical and technological advances but also represent major paradigm shifts in system theory. The main shift is away from the normative application of technology to change the world to be theoretically tractable, and towards increasing model realism. The limitations of classical "hard" system theory when applied to natural systems are the impetus behind the development of modern "soft" system theory, its foundations in fuzzy sets theory and its application in expert systems.

Keywords: systems theory, systems engineering, fuzzy sets, expert systems.

1. INTRODUCTION

Lotfi A. Zadeh first discussed the need for a "mathematics of fuzzy or cloudy quantities" in a paper entitled "From circuit theory to system theory" published in 1962. This led to his publishing his seminar paper, "Fuzzy sets", proposing such a mathematics in 1965. A comprehensive bibliography for the first decade shows an increase from 2 papers published in 1965 to over 227 in 1975 with a cumulative total in 1975 of some 620 items (Gaines and Kohout, 1977) and in 1979 of some 1400 items (Kandel and Yager, 1979). The number of papers a year and cumulative total fit well to exponential growth at 60% a year for the first decade. However, it is now almost impossible to track the growth of a literature which has grown from the output of a small group of specialists to that of an international community involving almost every nation and discipline. The growth rate of the dissemination of knowledge about, interest in, and work on fuzzy sets theory (FST) and its applications has been spectacular.

Why has there been this tremendous growth of interest in the past twenty years in the mathematics of fuzzy or cloudy quantities? What changes have occurred in systems engineering? This paper suggests that there has been a shift in the modes of thinking and problem-solving for a significant community of theoretical and applied scientists and technologists. The "hard"

systems approach that has proved so powerful in the development of man-made systems is far less useful in developing models for the management of natural systems, or coupled man-made and natural systems. A "soft" systems approach has become necessary to extend our science and technology to systems engineering for major ecological, social and economic processes.

Nowhere is the significance of this change more apparent than in the development of expert systems (ESs) where a soft systems approach has been taken to the encoding of human expertise for computer-based systems (e.g. Michie, 1979; Gevarter, 1983; and Reitman, 1984). This is an interesting area, not only for its high intrinsic value, but also because it enables us to contrast differing aspects of the role of FST in modern information science. Expert systems development leads to requirements for reasoning with imprecise data where FST provides an alternative paradigm to those of classical logic and probability theory. The most well-recognized breakthroughs in ESs such as MYCIN (Shortliffe, 1976) were not based on FST, but on heuristic methods that turn out to closely resemble FST. Other early breakthroughs such as linguistic process controllers (Mamdani and Assilian, 1981) were based directly on FST.

The next section outlines the development of ESs and the role of FST, and the following section considers the paradigm changes involved.

2. EXPERT SYSTEMS AND FUZZY SETS THEORY

The computer simulation of people in the roles of experts on some topic has become an important application of interactive computer systems. It has generated a new industry based on creating expert systems to make the practical working knowledge of a human expert in a specific subject area such as medicine or geology widely available to those without direct access to the original expert (Reitman, 1984). Programs now exist that have made practical achievements in medical diagnosis, interpretation of mass spectroscopy results, analysis of geological survey data, and other problems where one would normally go to a human expert for advice.

One of the first ES developments was the fuzzy logic control system developed in 1974 by Mamdani and Assilian. The system accepted human knowledge of control strategies expressed verbally and encoded it directly as computer programs which acted on the environment (Mamdani and Assilian, 1981). This work was undertaken as part of a study of machine learning in process control and the system controlled was a small steam engine. The verbal rules were of the form shown in Fig. 1.

IF the pressure error is positive and big and the change in pressure error is not negative medium or big
THEN make the heat change negative and big

Fig. 1. Rule from a fuzzy logic controller

What was surprising at the time and made the 1974 results

a recognized breakthrough was that the control rules derived from the verbal statements were extremely effective. They compared favorably with those derived by tuning a standard PID (proportional-integral-derivative) controller for optimum performance. It was also found that the learning machine then proceeded only to learn less effective strategies. Hence interest switched to the process whereby human expression of verbal rules that appear vague can lead to highly effective control strategies. In the past ten years Mamdani and Assilian's results have been replicated in many different countries for many different control processes, including a number of significant industrial processes such as pig iron smelting where effective automatic control had been thought to be impossible (Mamdani, Østergaard and Lembessis, 1984).

The concept of an ES was not prevalent at the time of the initial fuzzy control studies and their significance as examples of early ES development was noted only later. In parallel with the controller development, other rule-based ESs were being developed for completely different domains. The system widely recognized as an early breakthrough, MYCIN, is a medical diagnosis ES which aids a clinician to act as a consultant on infectious diseases (Shortliffe, 1976). It uses rules of the form shown in Fig. 2.

RULE 50
IF 1) the infection is primary-bacteremia, and
2) the site of the culture is one of the sterile sites, and
3) the suspected portal of entry of the organism is the gastro-intestinal tract,
THEN there is suggestive evidence (.7) that the identity of the organism is bacteroides

Fig. 2. A MYCIN rule

These rules are obtained from specialists in microbial infections and their application to particular data is fairly simple data processing. The rules are validated through their application to many cases and revised when they fail to give the correct diagnosis. MYCIN is designed to interact with a clinician in order to make a diagnosis and suggest therapy for a particular patient with suspected microbial infections. It first gathers data about the patient and then uses this to make inferences about the infections and their treatment.

Note that the MYCIN rule of Fig. 2 involves an assertion that is evidential rather than true. Shortliffe found it necessary to encode rules of inference that were imprecise and could not be encoded simply in terms of truth and falsity. He ascribed a verbal label, "suggestive evidence", and a numerical truth value, "0.7", to a rule and developed a calculus for combining such truth values in chains of logical inference. Thus, linguistic reasoning and multivalued logics were key components of early ES developments although the MYCIN developers were initially unaware of FST and the linguistic controller developers were initially unaware of ES concepts.

It was also discovered that the rule-based approach to knowledge encoding could be applied to high-level capabilities such as learning processes through the use of metarules. Mamdani, Procyk and Baaklini (1976) found that learning could be introduced effectively in the steam engine controller through metarules that expressed the way in which the basic rules should be changed as a result of performance feedback. The learning level of their controller operated on rules of the form shown in Fig. 3. This was sufficient for the fuzzy controller to acquire a control strategy similar to that induced through verbal rules from a human expert.

IF time is small and error is negative big
THEN desired change is big
IF time is big and error is positive zero
THEN desired change is zero

Fig. 3. Metarules from a fuzzy learning controller

Metarules were also introduced independently by Davis to aid the debugging of MYCIN. It was difficult to set up the MYCIN rules initially and also difficult to trace errors in the deductions. To overcome these problems TEIRESIAS (Davis and Lenat, 1982) was added as an auxiliary ES with expertise about MYCIN to explain MYCIN's decisions and help the clinician amend the rules when they lead to incorrect conclusions. TEIRESIAS uses a similar rule-based approach to reasoning as does MYCIN but the rules are now rules about the forms of rules and the use of rules. A typical such metarule is shown in Fig. 4. Whereas MYCIN's rules are specific to microbial infections, those of TEIRESIAS are more general and can be used in other domains. Davis (1983), for example, shows TEIRESIAS being used as an investment decision system for clients of a stockbroker.

METARULE003:
IF 1) there are rules which do not mention the current goal in their premise
2) there are rules which mention the current goal in their premise
THEN it is definite that the former should be done before the latter

Fig. 4. A TEIRESIAS metarule

One of the important features of MYCIN/TEIRESIAS that has become an essential characteristic of ES is their capacility to provide explanations of the deductions given. "Why?" questions are accepted as responses when data is requested and are interpreted as a request for the rule to be shown that requires the data requested. A "why?" question may also be asked when conclusions are drawn and this is interpreted as a request for the complete chain of logic used in arriving at that conclusion to be shown. The facility to answer such questions make ES accountable for their behavior and conclusions. This is itself a major new feature of systems programmed for computers.

Another important feature of ES is that they are not static representations of knowledge but can continue to acquire

knowledge as they are used. Essentially, the use of metarules allows ES to be programmed interactively by their users. From one perspective the metarules of the fuzzy learning controller and TEIRESIAS can be seen as an important development in automatic programming. From another they can be seen as a way in which a machine acquires knowledge through interaction with its environment or with a person. These are analogous to the fundamental ways in which people acquire knowledge (Gaines and Shaw, 1984a). For such applications computational logics capable of dealing with the uncertainties of imprecise data and fallible hypotheses are essential.

Since the early success with fuzzy logic control and MYCIN, a very wide range of ESs have been developed. Gevarter (1983) has summarized some well-known expert systems and their applications but the numbers and domains have since increased so rapidly that it is now impossible to make any accurate count. Most universities have some activity in this field and many industrial ESs are regarded as highly proprietary. ESs are a pragmatic example of the success of a soft systems approach based on linguistic reasoning with uncertain rules and data (Gaines and Shaw, 1984b). They contrast with previous unsuccessful approaches to similar problems based on the development of precise mathematical models and their use in the development of optimum control and decision algorithms.

The next section considers the significance of this change of approach.

3. SHIFTS IN SYSTEMS PARADIGMS

The previous section has shown how the early applications of FST to control and decision systems paralleled the development of early expert systems in the use of linguistic rules, fuzzy reasoning and metarules. This role of FST, significant as it is in itself, is only an indication of the deeper paradigm shifts from which FST and ES both stem. The classical approach in decision and control system design is shown in Fig. 5. This positivistic paradigm underlies the methodologies of the physical sciences and technologies based on them. It has the merit that it has been extremely successful in engineering much of the technological infrastructure of our current civilization.

However, this paradigm is successful only to the extent that the systems under consideration are amenable to instrumentation and modeling. Its greatest successes have been where this amenability can be achieved normatively, that is in cases where the system to be controlled is itself a human artifact. For example, linear system theory has not become a major tool in systems engineering because most natural systems are linear - they are not. The implication is in the opposite direction: that linear systems are mathematically tractable and that we design artificial systems to be linear so that we may model them readily.

The application of "a linear model with quadratic peformance criterion" to natural systems is often attempted but, in general, it does not work. We have done so not because the tool was appropriate, but because it was the only one we had. How-

STEP 1
Thoroughly instrument the system to be controlled or about which decisions are to be made

STEP 2
Use the instrumentation to gather data about the system behavior under a wide variety of circumstances

STEP 3
From this data build a model of the system that accounts for this behavior

STEP 4
From this model derive algorithms for decision or control that are optimal in terms of prescribed performance parameters

Fig. 5. The hard systems approach

ever, the use of a hammer to insert screws, although partially effective, tends to distort, destroy, and generally defeat the purpose of using a screw. Similarly, the use of an inappropriate system theory to model a system may give useful, but limited, results when we have no other, but it distorts reality, destroys information and generally defeats the purpose of modeling that system.

Much of our current technology succeeds to the extent that it is normative. In agriculture we reduce the complexity of a natural ecology to a comprehensible simplicity by the use of pesticides, herbicides and chemical fertilizers (Gaines and Shaw, 1984c). We reduce the system to one which is amenable to our modeling techniques. That simpler is not necessarily better and that re-engineering nature to impose uniformity destroys variety which is itself valuable have only been realised in recent years.

The four shifts in perspective that we see in FST and ES are shown in Fig. 6. The last three perspectives all stem from the first. The importance of this first perspective to Zadeh is apparent in his 1962 paper where he discusses the fundamental inadequacy of conventional mathematics for coping with the analysis of biological systems, noting also that the need for a new mathematics was becoming increasingly apparent even in the realm of inanimate systems.

The second perspective is that which lead to FST. Optimal control theory was regarded as the peak achievement of system theory in the 1950s and 1960s. However, it proved limited in application because it demanded precision in system modeling that was impossible in practice. It was too sensitive to the nuances of system structure expressed through over-precise system definition.

The third perspective is that which led to the success of linguistic fuzzy controllers and later ESs. Hayes-Roth (1984) has noted the many problems that have been felt to require human management are now amenable to ESs. Modeling the way the expert

PROBLEM 1
The models available are inadequate to capture the system

OLD APPROACH: PROCRUSTEAN DESIGN
Change the world to fit the model - normative technology

PARADIGM SHIFT: MODEL REALISM
Use system methodologies and information technology that enable the natural world to be modeled without distortion and destruction

PROBLEM 2
Optimal control is over-sensitive to system uncertainties

OLD APPROACH: SUB-OPTIMALITY
Use a sub-optimal controller that is robust

PARADIGM SHIFT: MODEL UNCERTAINTY
Model the uncertainty as part of the system

PROBLEM 3
Data is unavailable or inadequate for modeling

OLD APPROACH: MANAGE
Do not automate - leave to human decision/control

PARADIGM SHIFT: EXPERT SYSTEMS
Model the person as a decision-maker or controller

PROBLEM 4
Neither a human nor an automatic system alone is adequate

OLD APPROACH: AD HOC SYSTEM DESIGN
Use a mixture of automatic and human decision/control

PARADIGM SHIFT: ACCOUNTABLE INTEGRATION
Integrate automatic and human activity - make the automation accountable ("Why?" in ES)

Fig. 6. Paradigm shifts in systems engineering - from the hard to the soft systems approach

performs the task rather than modeling the task itself is the primary characteristic of an ES.

The fourth perspective is an important one for both ES and FST. They are knowledge-based systems because they make provision for explaining the decisions reached in terms of the data and inferences used. It is interesting to note that logics of uncertainty that aggregate evidence, such as probabilistic logics, do not provide a simple mechanism for explanation. Explicable logics have to be truth-functional and non-aggregative; fuzzy logic satisfies these requirements (uniquely among those logics satisfying the weak axioms of a standard uncertainty logic (Gaines, 1983)). It is also interesting to note that the

capability to give explanations is seen by some philosophers of science as a key difference between models that make accurate predictions and scientific theories that in addition provide causal explanations (Salmon, 1984). The "why?" question has important implications for both the practical and theoretical significance of ESs and the logics on which they are based.

4. CONCLUSIONS

FST was from the outset an attempt to create a new mathematical system theory that corresponds to Paradigm Shift 1 and fits the realities of the world without distorting them. It was created by a person who had extended the boundaries of current system theory, attempted to encompass in generality the key concepts of applied systems engineering (Zadeh, 1956, 1957, 1963 and 1964), and recognized the failure of that theory in this task. Developments in ES have shown the practical significance of this paradigm shift in enabling systems to be engineered for problems previously considered intractable. FST and ESs, and the application of one to the other, are not just mathematical and technological advances but also represent major paradigm shifts in system theory. This has involved fundamental changes in system philosophy and technology, shifts from a positivistic, normative approach to a more realistic and naturalistic approach. These shifts are apparent throughout science and technology and its application to our world and society.

Fuzzy sets theory cannot be either right or wrong. It is applicable mathematics tested by its uses. However, the rationale behind it, the systemic principles involved, can be right or wrong. They are right for our time, for the objectives of dealing adequately with a complex universe and extending the capabilities of the person with computer enhancements. The soft systems principles involved do not replace hard systems principles but extend the domain of systems theory to encompass both. The re-development of system theory is not yet complete and the seminal notions of stability, adaptivity, modeling, and so on, still need adequate expression. However, we now have the foundations on which to build a system theory that combines realism with power and provides applicable mathematics for our knowledge-based society.

The papers in this volume present the state-of-the-art of soft systems engineering based on FST, mainly in a decision making and optimization context, and its application to a wide variety of practical problems.

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