"A MODEL FOR TEMPORAL REASONING IN MEDICAL EXPERT SYSTEMS"

by

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A model for temporal reasoning in medical expert systems

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Abstract: While the results obtained with medical expert systems such as MYCIN, INTERNIST and CADIAG, have been very encouraging, they have some limitations which prevent them from fully simulating the behaviour of a medical expert. Some of these deficiencies are external (i.e. peculiar to the domain of application) while others are internal (i.e. caused by the technology used). This paper explains these limitations of medical expert systems and addresses the issue of temporal reasoning in medical expert systems. Temporal reasoning is specially important for medical expert systems as the final diagnosis is often strongly affected by the sequence in which the symptoms develop. Current research on time structures in computer science is reviewed and a temporal model based on fuzzy set theory is developed. The proposed model allows a simple and natural representation of symptoms and provides for efficient computation of temporal relationships between symptoms. The applicability of the proposed temporal model to reasoning in expert systems is demonstrated.

Keywords: diagnosis, expert systems, medical applications, symptoms, temporal reasoning.

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1 INTRODUCTION

The concept of time plays an important role in our life and thus it is natural that temporal knowledge is required in a wide range of disciplines including computer science, business, engineering, psychology, philosophy and linguistics. Within computer science, the problem of representing temporal knowledge and temporal reasoning arises in databases, artificial intelligence, program verification and other areas involving process modelling. In artificial intelligence, most problem solving models must be capable of capturing the change associated with the real world. For example, changes in the environment with time have to be represented and manipulated effectively in order to plan a robot's actions. Most databases have to be updated with time and it is necessary to store the *history*, i.e., a record of all the updates, to be able to answer queries like: *How many apples have been shipped between January 1987 and October 1987?* In some fields, for example medicine, it is vital to represent temporal information effectively as the time course of events is a critical part of the data.

Early work in computer based medical systems usually concentrated on statistical approaches like Bayesian models [26], discriminant analysis [25] and cluster analysis [23]. Lately principles from artificial intelligence (AI) have been used for building medical expert systems. Notable examples of such medical expert systems are MYCIN [29], INTERNIST [22,24] and CADIAG [1]. While the results obtained with these medical expert systems have been very encouraging, they have some limitations which prevent them from fully simulating the behaviour of a medical expert [2,6,11]. Some of these deficiencies are external (e.g. lack of proper documentation of diagnoses and influence of previous therapy) while others are internal (e.g. inability to handle uncertainty effectively and lack of temporal reasoning techniques). In this paper we address the issue of temporal reasoning in expert systems. This is particularly important for medical expert systems as the diagnosis is often strongly affected by the temporal relationships between a patient's symptoms. We develop a model based on fuzzy set theory [32–35] for representing temporal relationships between symptoms and demonstrate its applicability to expert systems.

This paper contains five other sections. Section 2 provides a brief review of expert systems (with special emphasis on medical expert systems) and explains some of their deficiencies. Section 3 briefly reviews some of the currently popular temporal models in AI research. Sections 4 and 5 form the core of this paper. Section 4 describes our proposed temporal model and section 5 discusses its implementation in expert systems. Section 6 concludes the paper.

2 MEDICAL EXPERT SYSTEMS

Feigenbaum, a pioneer in expert systems, has described expert systems as 'intelligent computer programs that use knowledge and inference procedures to solve problems requiring significant human expertise for their solution' [14]. The basic structure of a conventional expert system (Figure 1) consists of:

1 A knowledge base consisting of domain facts and heuristics usually expressed as a collection of IF . . . THEN rules.
2 An inference engine (control structure) for using the knowledge base in the solution of the problem.
3 A working memory for keeping track of the problem status, the input data and the relevant history of the solution thus far done.

Expert systems differ from conventional computer programs [12] in that there is a clear separation of the knowledge base, inference engine and the working memory. The program itself is only an interpreter, or a general reasoning mechanism, and ideally the system can be changed by simply adding or deleting rules in the knowledge base.

Due to the importance and specialised nature of medical diagnosis, medicine is an ideal domain for testing expert systems. Starting in the 1970s, several medical expert systems have been designed. These systems have had dramatic successes which helped to contribute to an expanding wave of activity in expert systems. There has been considerable research in the development of expert systems and today it is possible to take a commercial expert system building tool (e.g. KEE and ART) off the shelf and build an expert system in a matter of a few weeks. Despite the tremendous success and popularity of medical expert systems, they have certain limitations, both *external* and *internal*. Below we list some of these deficiencies. While the list is representative, it is by no means exhaustive. Some of the external deficiencies are:

1 The case histories of patients are usually incomplete and in some cases even wrong as patients often forget many causally connected symptoms.
2 The influence of previous drug therapy can modify the course of a disease in several ways and complicates the diagnosis.
3 The documentation of diagnoses is also not entirely satisfying. This is particularly true when there is an overlap of diagnoses, e.g. overlapping syndromes in connective tissue diseases.
4 The definition of normal ranges for physical tests depends on several factors, e.g. the normal range for the mobility of the lumbar spine changes with age.
5 Most disease symptoms are *fuzzy* concepts, e.g. pain is better defined by the degree of intensity of the pain rather than by the boolean values 'yes/no'. Most conventional expert systems are built around classical boolean logic and cannot handle such fuzzy concepts naturally.

Some of the internal deficiencies are:

1 Few current expert systems deal satisfactorily with uncertainty, e.g. MYCIN uses an *ad hoc* approach of certainty factors. A sound treatment of uncertainty is crucial as most real world concepts (e.g. pain and intelligence) are too imprecise and/or too complex to be susceptible of precise mathematical formulations. Lately, uncertainty and evidential reasoning have been researched widely in artificial intelligence and some mathematical theories (e.g. fuzzy reasoning, Dempster-Shafer and non-monotonic logic) have been developed, but thus far, with a few exceptions (e.g. CADIAG-II), there has been 'poor technology transfer' from the domain of pure research to practical, working expert systems.

2 Limited provision of a model for dealing with temporal relationships. This is specially important for expert systems

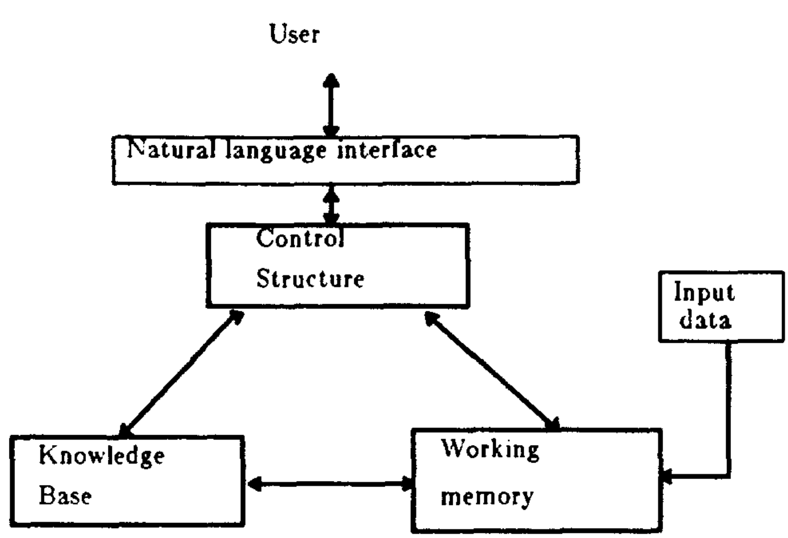

Figure 1 *Structure of an expert system.*

operating in domains such as medicine where the temporal relationships between symptoms strongly affect the diagnosis.
3 Limited support for spatial reasoning. This is important for systems which interact with complex realistic external environments.
4 Little provision for genuine distributed problem solving.
5 Poor support for managing internal conflict. Contemporary expert systems usually lack good tools for detecting and dealing with conflicting data, conflicting rules and conflicting user-models.
6 Nearly all contemporary expert systems are built on classical two-valued logic and require exact matching of the premises of the rules with the knowledge base. When the input data fails to match the premises of the rules, the expert system fails to produce an answer. One solution to this problem is to use *fuzzy rules* (see Section 5) which allow the expert system to produce an answer in the absence of exact matching of the premises.
7 Most expert systems do not have a *learning* component to learn and automatically modify with experience the rules in the knowledge base.

3 TEMPORAL MODELS

In this section we first describe the two basic symbolic models of time and then provide a brief review of some of the relevant aspects of previous research in temporal data representation and manipulation.

3.1 Temporal representation: states vs intervals

Recent research in temporal reasoning has given rise to two basic symbolic models of time. In the first approach, the basic unit of time is an atemporal entity called a *state* or an *instant*. A state is a description of the world at an instantaneous point in time. In the second approach, the basic unit is the interval, which represents a finite 'chunk' on some time line. In the state based approach, the passage of time is represented by a partial ordering on the states. An interval of time is thus represented using a set of states. Intervals are the primitives in the second approach and points or instants of time can be defined using intersection of intervals [4]. Thus we see that these two models are equivalent. Tsang [31] and Ladkin [19] have formally proved this equivalence. Both these approaches can be modelled in conventional data models. For example, in the context of a relational data model, a state corresponds to a *snapshot* of a relation and successive states correspond to successive snapshots. A major disadvantage of storing successive snapshots is obvious: a large amount of memory may be wasted. Another disadvantage is that events are defined indirectly as facts that are true over a consecutive set of states. Thus temporal relationships between events have to be determined by examining the set of states associated with each of the events. On the other hand, in interval based logic, events can be directly associated with intervals and the temporal relationships between events can directly be expressed as interval relationships [4]. Such a representation is not only more convenient, it is also more natural as most events occur over intervals of time. Some events do seem to occur instantaneously, but as Allen [4] has argued, even seemingly instantaneous events can be seen to occur over intervals once we 'turn up the magnification' sufficiently high. Thus intervals are a powerful abstraction for representing temporal knowledge. Our proposed temporal model shall be based on intervals.

3.2 Review of relevant literature

Bruce's [7] pioneering work in temporal representation was primarily concerned with the computational linguistic aspects of temporal inference. Kahn [17] designed and implemented a module called the 'time specialist' to store, retrieve and reason about temporal information. He used intervals to represent fuzzy time information, e.g. 'several days' was represented as an interval (2,6), and suggested a tubular method for dealing with fuzzy inference. Scheng [28] developed a fuzzy temporal logic for the manipulation of fuzzy linguistic temporal quantifiers such as 'a few days ago', 'eventually' and 'often'. Malik and Binford [20] converted temporal specifications into inequalities and used mathematical techniques such as linear programming for inferencing. Allen [4] developed his temporal model by taking time intervals as primitives and defining relationships between intervals. He used constraint propagation techniques along with a hierarchical organisation of intervals to maintain temporal relationships. McDermott [21] proposed a state based temporal logic using the possible world approach. His model provides a method for the analysis of causality, continuous change in quantities and the persistence of facts.

Bubenko [8] developed his temporal model in the context of database systems by adding an additional field of temporal validity to each tuple in database relations for temporal information. Clifford and Warren [9] used intensional logic to define the formal semantics of time in database systems. Their primary idea was to represent time varying attributes of a database as functions from a set of times into values. Gadia [15] has proposed a homogeneous model for temporal databases within the framework of classical relational database theory. The model is realised as a temporal parameterisation of static relations. Segev and Shoshani [27] have defined the temporal concept of a time sequence, which is basically the sequence of values in the time domain for a single entity instance. They have identified the semantic properties of these time sequences and defined operations over them. Clifford and Tansel [10] have described a non-first normal extension to the relational model for handling temporal data and have developed some of the relevant algebra.

4 SYMPTOM-BASED TEMPORAL MODEL

In this section, we describe our proposed temporal model.

I represents the set of time intervals. Small letters i,j,k, ... or i_1, i_2 ... refer to individual intervals. For simplicity we assume that the intervals $i, i\epsilon I$ are disjoint in time. We place no other restriction on the construction of the time intervals. The construction of the time intervals shall depend on the granularity of the relevant symptoms and shall affect the discrimination in the results.

E represents the universe of events. Small letters e,f,g, ... or $e_1, e_2, \ldots, e_m$ refer to individual events. In the context of medical expert systems, events correspond to symptoms and/or results of various laboratory tests. In the following discussion, we shall use the terms events and symptoms interchangeably. The proposed temporal logic can be used for reasoning about appropriately defined events in any expert system. Events are represented as fuzzy sets over the universe I, the membership function [35,40] defining the degree to which an event occurs in a given time interval. The degree to which an event e occurs in interval i is given by $\mu_i(e)$, $0 \le \mu_i(e) \le 1$. $\mu_i(e)$ can alternatively be interpreted as the intensity of the occurrence of the symptom corresponding to event e in interval i, measured on a scale of 0 to 1. If $\mu_i(e) = 0$, then symptom e does not occur in interval i. Similarly if $\mu_i(e) = 1$, then symptom s occurs to its highest degree of manifestation in interval i.

Definition: An event (symptom) is defined by the *degree* of its occurrence in any interval $i, i\epsilon I$. Formally,

$$e = \cup_{i\epsilon I} \{ <i, \mu_i(e)> \}$$

Such a definition of symptoms is simple and naturally captures their fuzzy nature.

Example 1: Consider the following simple (edited) facts taken from a patient's hospital admission record:

'Since three weeks, X was noticing a slight swelling of her right foot accompanied by a light pain. About 3 days ago the swelling increased and there was some pus formation and increased pain. At the same time, she started experiencing some fever. Since this morning she has high fever, acute pain and swelling of her foot accompanied by substantial pus formation.'

Here we can choose the time intervals as

i_1 = the first two and a half weeks,
i_2 = the next three days,
i_3 = today,

and define the symptoms as

e_1 = swelling of foot = $\{(i_1, 0.3), (i_2, 0.8), (i_3, 0.9)\}$
e_2 = pain in foot = $\{(i_1, 0.2), (i_2, 0.7), (i_3, 0.9)\}$
e_3 = pus formation in foot = $\{(i_2, 0.3), (i_3, 0.8)\}$
e_4 = fever = $\{(i_2, 0.3), (i_3, 0.8)\}$

Comment 4.1: As stated earlier there is considerable freedom in the choice of the granularity of the intervals. Normally, the granularity of the occurrence of the symptoms shall govern the construction of the time intervals, e.g. if in the above example a description of the symptoms were given on a day-to-day basis, then we might find it more useful and natural to define each day as a separate interval of time. In some cases, the physician may find it necessary to choose some particular time interval, e.g. the reaction time to a particular drug. The construction of these time intervals shall determine the specificity of the results, and this shall become more clear when we define the operators for determining temporal relations between symptoms.

In the above definition of symptoms we have implicitly defined them a type-I fuzzy sets [35], i.e. fuzzy sets whose membership functions are crisp numbers in the range [0,1]. A more natural definition of symptoms is to define them as type-II fuzzy sets [35], i.e. allow the membership functions to be fuzzy sets themselves. Thus we can now define our symptoms as

e_1 = $\{(i_1$, slight), $(i_2$, much), $(i_3$, very much)$\}$,
e_2 = $\{(i_1$, slight), $(i_2$, much), $(i_3$, very much)$\}$,
e_3 = $\{(i_2$, some), $(i_3$, much)$\}$,
e_4 = $\{(i_2$, some), $(i_3$, much)$\}$,

where *slight*, *much*, *very much* and *some* are fuzzy sets on [0,1]. A possible definition of these fuzzy sets is shown in Figure 2. In the term *very much*, *very* can be considered as a linguistic hedge [35] of the fuzzy set *much* and the membership function of *very much* can be obtained by the operation of *concentration* (squaring) [35] on μ_{much}, the membership function of *much*, i.e.

$$\textit{very much} = \int_U \mu^2_{much}(u)/u$$

Where U = [0,1]. Various other linguistic hedges are possible, e.g. *more or less*, *not*, *etc.*, and suitable modification functions are available for these linguistic hedges in fuzzy set literature [35].

Defining the values of symptoms as type-II fuzzy sets allows us to have a more useful and natural description of symptoms. It saves the physician the (often unnatural) effort of ascribing numbers to the intensity of the occurrence of symptoms and allows for a natural encoding of verbal linguistic descriptions into a computational representation. For simplicity, in the following analysis, we shall only

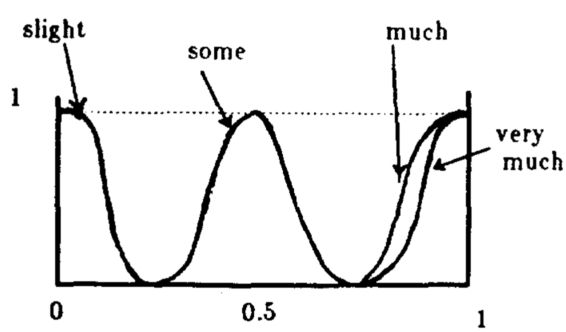

Figure 2 *Linguistic hedges.*

consider type-I fuzzy sets, although the definitions can be extended to cover type-II fuzzy sets also.

4.1 Temporal operators for events

Temporal operators for events can be classified into two broad categories:

1 Unary operators: which operate on only one event (e.g. *how long did John have a fever*?).
2 Binary operators: which operate on two events (e.g., determining the *precedence of symptoms*).

We shall consider three different unary operators for events, namely the *begin* operator B_e, the *end* operator E_e and the *duration* operator D_e. B_e (E_e) gives the interval during which event e started (ended) and D_e gives the duration of event e. We shall consider eight different binary temporal operators for events and their crisp definitions are illustrated in Figure 3.

As mentioned earlier, we can represent an event e as a fuzzy set:

$$e_j = \cup_{i \in I} \{ < i, \mu_i(e) > \}.$$

The support set of an event, S_e, is the set of all intervals, i, $i \in I$, such that $\mu_i(e) > 0$, i.e. the event has a positive degree of occurrence for that interval i.

$$S_e = \cup_{i \in I, \mu_i(e) > 0} \{ < i > \}.$$

Note that $\mu_i(e) = 0$ for all intervals i, $i \in (I - S_e)$. For i, $i \in I$, let i_- and i_+ represent the time of the beginning and end of interval i. For $i \in S_{e_1}$, let L and U represent the beginning and the end of the first and the last interval, respectively, i.e. all the intervals in S_{e_1} lie within the range $[L, U]$. Now for any interval i, $i \in S_{e_1}$, $p_-(i)$ and $p_+(i)$ are measures of the proximity of i to L and U, respectively, where

$$p_-(i) = \frac{(i_-) - L}{U - L} \quad \text{and} \quad p_+(i) = \frac{U - (i_+)}{U - L}.$$

Now we are ready to define the various temporal operators.

4.2 Unary temporal operators

As mentioned earlier, we consider three operators: *begin* (B_e), *end* (E_e) and *duration* (D_e).

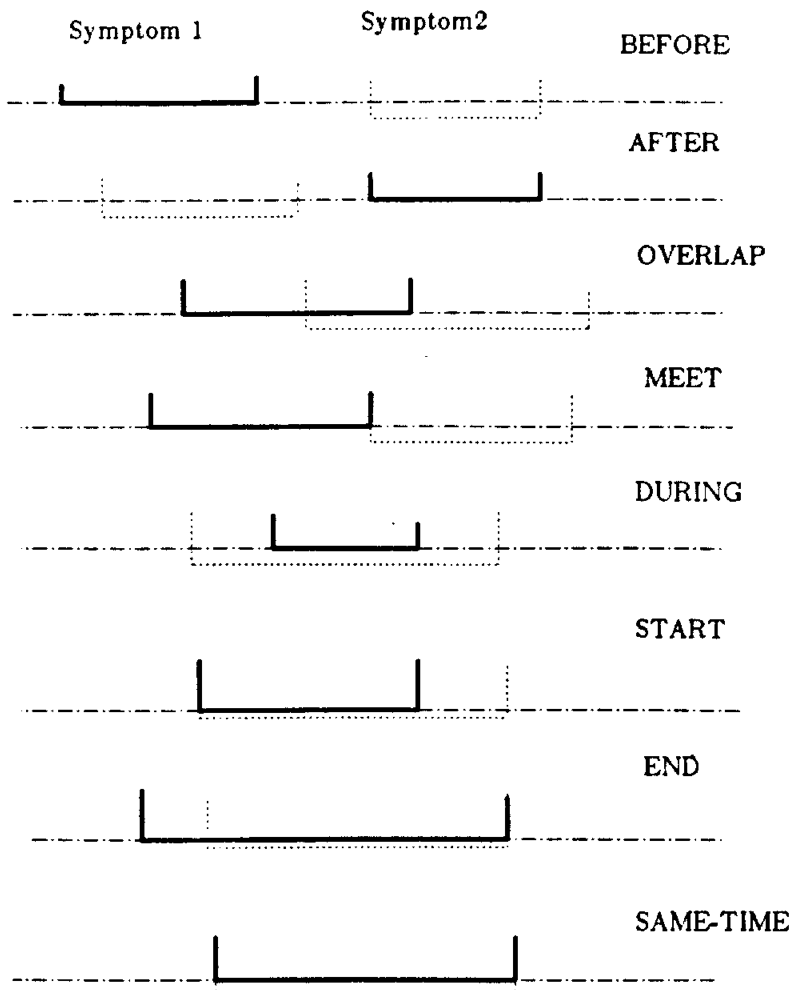

Figure 3 *Temporal relationships between events.*

Begin: An event e is said to start in interval i', i.e. B_e has the value i', where

$$(1-p_-(i'))\ \mu_{i'}\ (e) \geq \max_{i \in (S_e - i')} (1-p_-(i))\mu_i(e).$$

End: An event e is said to end in interval i', i.e. E_e has the value i' where

$$(1-p_+(i'))\mu_i{}'\ (e) \geq \max_{i \in (S_e - i')} (1-p_+(i))\mu_i(e).$$

Duration: The duration D_e of an event e is defined as

$$D_e = E_{e_+} - B_{e_-}$$

4.3 Binary temporal operators

For capturing the different temporal relationships between events, we define eight *temporal relational operators*: $<, >$, o, m, d, s, x and $=$.

$<$ is the precedence operator and $\mu_<(e_1,e_2)$ gives the degree to which e_1 temporally precedes e_2.
$>$ is the inverse operator of $<$ and $\mu_>(e_1,e_2)$ gives the degree to which e_1 follows e_2.
o is the *overlap* operator and $\mu_0(e_1,e_2)$ gives the degree to which events e_1 and e_2 overlap in time.
m is the *meet* operator and $\mu_m(e_1,e_2)$ gives the degree to which event e_1 meets, i.e. immediately precedes, event e_2.
d is the *during* operator and $\mu_d(e_1,e_2)$ gives the degree to which event e_1 occurs during event e_2.
s is the *start* operator and $\mu_s(e_1,e_2)$ gives the degree to which events e_1 and e_2 start together in time.
x is the *end* operator and $\mu_x(e_1,e_2)$ gives the degree to which events e_1 and e_2 end together in time.
$=$ is the *same-time* operator and $\mu_=(e_1,e_2)$ gives the degree to which events e_1 and e_2 begin and end at the same time.

Note that for $\psi \in \{<,>,o,m,d,s,x,=\}$, $0 \leq \mu_\psi(e_1,e_2) \leq 1$. The $>$ operator is redundant (it is the inverse of $<$), but we retain it for clarity of presentation. Before giving a formal definition for these temporal operators, we need to define certain relations on intervals.

$$\xi_p(i_1,i_2) = 1 \quad \text{iff} \quad i_{1+} < i_{2-}$$
$$= 0 \quad \text{else}$$

i.e. $\xi_p(i_1,i_2) = 1$ iff i_1 ends before i_2 begins.

$$\xi_f(i_1,i_2) = 1 \quad \text{iff} \quad i_{1-} > i_{2+}$$
$$= 0 \quad \text{else}$$

i.e. $\xi_f(i_1,i_2) = 1$ iff i_2 ends before i_1 begins.

$$\xi_w(i_1,i_2) = 1 \quad \text{iff} \quad i_{1+} < i_{2-}\ \&\ (\exists i \epsilon I)(\xi_p(i_1,i) = 1\ \&\ \xi_f(i_2,i) = 1)$$
$$= 0 \quad \text{else}$$

i.e. $\xi_w(i_1,i_2) = 1$ iff there does not exist another time interval i, $i \epsilon I$ between the end of i_1 and the beginning of i_2.

Note that these relations on intervals are easy to compute as a partial ordering of the intervals in time always exists (the intervals are disjoint). Now we can define the various operators.

$$\mu_<(e_1,e_2) = \max_{i_j \epsilon S_{e1}, i_k \epsilon S_{e2}, \xi_p(i_j,i_k)=1} (\min(\mu_{i_j}(e_1),\mu_{i_k}(e_2)))$$
$$\mu_>(e_1,e_2) = \max_{i_j \epsilon S_{e1}, i_k \epsilon S_{e2}, \xi_f(i_j,i_k)=1} (\min(\mu_{i_j}(e_1),\mu_{i_k}(e_2)))$$
$$\mu_m(e_1,e_2) = \max_{i_j \epsilon S_{e1}, i_k \epsilon S_{e2}, \xi_w(i_j,i_k)=1} (\min(\mu_{i_j}(e_1),\mu_{i_k}(e_2)))$$
$$\mu_0(e_1,e_2) = \max_{i \epsilon S_{e1} \cap S_{e2}} (\min(\mu_i(e_1),\mu_i(e_2)))$$
$$\mu_d(e_1,e_2) = \frac{\mu_0(e_1,e_2)}{\max_{i \epsilon S_{e1}} \mu_i(e_1)}$$
$$\mu_s(e_1,e_2) = \max_{i \epsilon S_{e1} \cap S_{e2}} (1-p_-(i))\min(\mu_i(e_1),\mu_i(e_2))$$
$$\mu_x(e_1,e_2) = \max_{i \epsilon S_{e1} \cap S_{e2}} (1-p_+(i))\min(\mu_i(e_1),\mu_i(e_2))$$
$$\mu_=(e_1,e_2) = \min(\mu_s(e_1,e_2),\mu_x(e_1,e_2))$$

We have used the standard *max* and *min* operators of fuzzy set theory while defining the above binary temporal operators. These definitions shall become clear from Example 2. It can be verified that the proposed definitions for the various temporal operators give the expected correct answer for the crisp conventional definition of events. The proposed definitions for these operators are based on an intuitive extension of the crisp definitions. It is possible to provide alternative definitions for these operators which may be more meaningful in special situations.

Example 2: We illustrate the above temporal operators in a temporal database storing information about the symptoms observed in patients. We consider the case of one patient, say someone named John. We further consider only three symptoms: *fever, cold* and *body-ache*. We represent the observed values of these events for John over time in Table 1. The unit of time is a day and we start the time scale at some arbitrary day termed 0. For compactness, we have given the values of the various symptoms for groups of days rather than for each day separately, and for simplicity we have kept the chosen intervals contiguous (this is not necessary). Now we can compute the various temporal relations between the events.

The degree to which e_3 precedes e_1, $\mu_<(e_3,e_1)$ is

$$\mu_<(e_3,e_1) = \max\ (0.2,\ 0.7,\ 0.2,\ 0.7,\ 0.2,\ 0.2) = 0.7.$$

Table 1

		e_1	e_2	e_3
	Interval	*Fever*	*Cold*	*Body-ache*
i_1	[0,3]	0	0.2	0.9
i_2	[3,5]	0.2	0.8	0.8
i_3	[5,7]	0.7	0.6	0.4
i_4	[7,10]	0.2	0.2	0.3

Similarly,

$$\mu_{<}(e_3,e_2) = \max(0.8, 0.6, 0.2, 0.6, 0.2, 0.2) = 0.8$$

$>$ is the inverse operator of $<$ and thus

$$\mu_{>}(e_1,e_3) = \mu_{<}(e_3,e_1) = 0.7$$

and

$$\mu_{>}(e_2,e_3) = \mu_{<}(e_3,e_2) = 0.8.$$

The temporal relations *after*, *meet*, *overlap*, and *during* can be computed in a similar manner. Some examples are given below:

$$\mu_{\mathrm{m}}(e_3,e_2) = \max(0.8, 0.6, 0.2) = 0.8,$$

$$\mu_{\mathrm{m}}(e_3,e_1) = \max(0.2, 0.7, 0.2) = 0.7,$$

$$\mu_{\mathrm{m}}(e_2,e_1) = \max(0.2, 0.7, 0.2) = 0.7,$$

$$\mu_{\mathrm{o}}(e_3,e_2) = \max(0.2, 0.8, 0.4, 0.2) = 0.8,$$

$$\mu_{\mathrm{o}}(e_3,e_1) = \max(0.2, 0.4, 0.2) = 0.4,$$

$$\mu_{\mathrm{o}}(e_1,e_2) = \max(0.2, 0.6, 0.2) = 0.6,$$

$$\mu_{\mathrm{d}}(e_1,e_2) = 0.6/0.7 = 0.86.$$

For any two of the temporal entities chosen out of e_1,e_2 and e_3 in this example,

$$L = 0 \quad \text{and} \quad U = 10$$

Also,

$$p_-(i_1) = 0; \quad p_+(i_1) = 0.7,$$

$$p_-(i_2) = 0.3; \; p_+(i_2) = 0.5,$$

$$p_-(i_3) = 0.5; \; p_+(i_3) = 0.3,$$

$$p_-(i_4) = 0.7; \; p_+(i_4) = 0.$$

Thus

$$\mu_s(e_1,e_2) = \max(0.7 * 0.2, 0.5 * 0.6, 0.3 * 0.2) = 0.3,$$

$$\mu_s(e_2,e_3) = \max(1 * 0.2, 0.7 * 0.8, 0.5 * 0.4, 0.3 * 0.2) = 0.56,$$

$$\mu_x(e_2,e_3) = \max(0.3 * 0.2, 0.5 * 0.8, 0.7 * 0.4, 1 * 0.2) = 0.4,$$

$$\mu_x(e_2,e_1) = \max(0.3 * 0, 0.5 * 0.2, 0.7 * 0.6, 1 * 0.2) = 0.42,$$

$$\mu_{=}(e_2,e_3) = \min(\mu_s(e_2,e_3),\mu_x(e_2,e_3)) = 0.4.$$

A simple check reveals that these temporal operators do give intuitively correct values for the various temporal relations.

4.4 Compound temporal events

We use the term *compound temporal event* or simply *compound event* to refer to a combination of events. Examples of compound events are (for the events given in Table 1): fever *and* body-ache, cold *or* fever, *no* fever, etc. (where we have dropped the qualifying adjectives). There are cases where we desire to determine temporal relations between compound events (e.g. whether John had a body-ache *during* the time he had a *cold* and a *fever*). We present below a set of definitions for the complementation, intersection and union of events.

4.4.1 Complement of an event

The complement of an event e_c is defined as

Definition:

$$e_c = \cup_{i \in I} \{ < i, 1 - \mu_i(e) > \}.$$

The complement of an event is also an event.

Example 3: For the events in Table 1:

$$e_{1_c} = \{(i_1,1), (i_2,0.8), (i_3,0.3), (i_4,0.8)\}$$

e_{1_c} can be interpreted as the compound event 'no fever', i.e. the symptom of *not* having fever.

4.4.2 Intersection of events

The intersection of e_1 and e_2 is defined iff $S_{e_1} \cap S_{e_2} \neq \Phi$. If $S_{e_1} \cap S_{e_2} = \Phi$ then $e_1 \cap e_2$ is not defined.

Definition:

$$e_1 \cap e_2 = \cup_{i \in S_{e_1} \cap S_{e_2}} \{ < i, \min(\mu_i(e_1), \mu_i(e_2)) > \}.$$

Temporal events are also closed under intersection. An example shall help to clarify the above definition.

Example 4: For the temporal data given in Table 1:

$$e_2 \cap e_3 = \{(i_1,0.2),(i_2,0.8),(i_3,0.4),(i_4,0.2)\}.$$

The compound event $e_2 \cap e_3$ can be interpreted as the complex symptom of having both a cold *and* a body-ache.

4.4.3 Union of events

Definition:

$$e_1 \cup e_2 = e = \cup_{i \in S_{e_1} \cup S_{e_2}} \{ < i, \max(\mu_i(e_1), \mu_i(e_2)) > \}.$$

The union of events is also closed. Again we provide an illustrative example to clarify the definition.

Example 5: We use the temporal data of Table 1. The complex symptom of either having fever *or* a cold can be represented by the compound event, $e_1 \cup e_2$:

$$e_1 \cup e_2 = \{(i_1,0.2),(i_2,0.8),(i_3,0.7),(i_4,0.2)\}.$$

4.5 Temporal operators for compound events

From the previous sub-section, we note that events are closed under complementation, union and intersection. Thus the temporal operators discussed above can also be applied to compound events. The following example shall help to illustrate the idea.

Example 6: We continue with the temporal data used in

Example 2 and the compound events defined in Examples 3–5. Suppose we desire to compute the degree to which e_3 (the symptom *body-ache*) precedes $e_1 \cup e_2$ (the compound symptom: *fever or cold*). The desired answer is given by $\mu_<(e_3, e_1 \cup e_2)$

$$\mu_<(e_3, e_1 \cup e_2) = \max(0.8, 0.7, 0.2, 0.7, 0.2, 0.2) = 0.8.$$

The degree to which e_3 occurs before $e_1 \cap e_2$ (the compound symptom: *fever and cold*) is given by $\mu_<(e_3, e_1 \cap e_2)$

$$\mu_<(e_3, e_1 \cup e_2) = \max(0.2, 0.6, 0.2, 0.6, 0.2, 0.2) = 0.6.$$

The degree to which e_1 (the symptom *fever*) occurs after $e_2 \cup e_3$ (the compound symptom *body-ache or cold*) is given by $\mu_>(e_1, e_2 \cup e_3)$

$$\mu_>(e_1, e_3 \cup e_2) = \max(0.2, 0.7, 0.2, 0.7, 0.2, 0.2) = 0.7.$$

Similarly, other temporal operators can be applied. The point to be noted here is that the simplicity of the adopted model enables us to combine events and apply temporal operators to them easily. Such a power of representation is difficult to achieve in other temporal data models.

To summarise, the advantages of our proposed temporal model are:

1 Simple and natural representation of symptoms.
2 Simple but powerful calculus for the manipulation of complex symptoms.
3 Efficient and easy calculation of the various temporal relations between both symptoms and complex symptoms.

The disadvantages of our proposed model are:

1 Difficult to decide upon the right granularity of time intervals.
2 Discrimination in results affected by the granularity of time intervals.

5 TEMPORAL REASONING IN EXPERT SYSTEMS

Most expert systems are rule based. A typical rule has the form

if s_1 and s_2 and ... and s_n then d_1 and d_2 and ... d_m

where $s_1, s_2, \ldots, s_n$ are premises and $d_1, d_2, \ldots, d_m$ are conclusions. In the context of a medical expert system, the premises are usually symptoms and/or results of various laboratory tests and the conclusions are the various diagnoses. Most expert systems are based on binary valued boolean logic, and thus the rules require an exact match on the premises. However, as mentioned in Section 2, most symptoms in medicine are fuzzy concepts, and thus we would like to have the ability to perform *fuzzy matching* of the premises when the input patient symptoms do not match exactly with the premises. We can achieve this by using *fuzzy rules* [35]. Consider a collection of fuzzy rules of the form

```
IF    [1]X1 IS R1, AND
      [2]X2 IS R2, AND
      ...
      [N]Xn IS Rn
THEN  [1]Y1 IS D1, AND
      [2]Y2 IS D2, AND
      ...
      [M]Ym IS Dm
```

which can be arranged in the form of a decision table shown in Table 2. Here $X_1, X_2, \ldots,$ are input variables (premises) and $Y_1, Y_2, \ldots,$ are the output variables (conclusions). Each row of the table represents a fuzzy rule in our expert system. It should be noted that a fuzzy rule is a more general version of the conventional IF ... THEN rule based on boolean logic. In general the values R_{ij} and D_{ij} are fuzzy sets. Now given a premise n-tuple $(R_1, \ldots, R_n)$, where $R_i, i \epsilon [1,n]$ is a fuzzy subset of the corresponding domain U_i of X_i, we would like to obtain the value of the conclusions $D_1, \ldots, D_m$ expressed, in general as a fuzzy subset of $V_i, i \epsilon [1,m]$, where V_i is the domain of the corresponding Y_i. A possible approach is to calculate the consistency of the input premise n-tuple with the premises of the various rules. Let τ_{ij} represent the degree of consistency of premise R_j with the R_{ij} element of a rule, $i = 1, \ldots, k$ and $j = 1, \ldots, n$. τ_{ij} is defined as

$$\tau_{ij} = \max(R_{ij} \cap R_j)$$
$$= \max_{u_j}[\mu_{R_{ij}}(u_j) \wedge \mu_{R_j}(u_j)]$$

in which $\mu_{R_{ij}}$ and μ_{R_j} are the membership functions of R_{ij} and R_j, respectively, u_j is a generic element of U_j, and '$\wedge$' represents the 'min' operator. In the above definition we have explicitly assumed that both R_j and R_{ij} are fuzzy sets. We have two more possibilities,

1 Either one of R_j or R_{ij} are crisp: Assume without loss of generality that R_j is crisp ($= a, a \epsilon U_j$) and R_{ij} is a fuzzy set with membership function $\mu_{R_{ij}}$.

Then we can define the consistency τ_{ij} as

$$\tau_{ij} = \mu_{R_{ij}}(a)$$

2 Both R_j and R_{ij} are crisp. This is the classical case. Let $R_j = a$ and $R_{ij} = b$, where a and $b \epsilon U_j$. Then we can define τ_{ij} as

$$\tau_{ij} = \frac{1}{1 + \beta(|a - b|)}$$

where β is a domain dependent constant.

Table 2

X_1	X_2	.	X_n	Y_1	Y_2	.	Y_m
R_{11}	R_{12}	.	R_{1n}	D_{11}	D_{12}	.	D_{1m}
R_{21}	R_{22}	.	R_{2n}	D_{21}	D_{22}	.	D_{2m}
—	—	—	—	—	—	—	—
R_{k1}	R_{k2}	.	R_{kn}	D_{k1}	D_{k2}	.	D_{km}

Now we can calculate the overall degree of consistency, τ_i, of the input premise n-tuple with the ith row of Table 2, $i = 1, \ldots, k$ by using the $\wedge$(min) operator as the aggregation operator. Thus

$$\tau_i = \tau_{i1} \wedge \tau_{i2} \wedge \ldots \wedge \tau_{i_n}$$

Then the desired expression for Y_i can be written as a linear combination of the D_{ji}, $j = 1, \ldots, k$, using the τ_i as the weighting coefficients

$$Y_i = \tau_1 \wedge D_{1i} + \tau_2 \wedge D_{2i} + \ldots + \tau_k \wedge D_{ki}$$

where + denotes union and $\tau_i \wedge D_{ji}$ is a fuzzy set defined by

$$\mu_{\tau_i \wedge D_{ji}}(v_i) = \tau_i \wedge \mu_{D_{ji}}(v_i)$$

for $j = 1, \ldots, k$.

Example 7: Let us demonstrate the above ideas with an example. A simple fuzzy rule incorporating temporal information is:

IF [1] PATIENT HAS PERSISTENT COLD BEFORE HIGH FEVER
AND [2] HIGH FEVER WITH ACUTE HEADACHE
THEN [1] PATIENT HAS ACUTE SINUSITIS

We can represent the above rule in the form of a table (Table 3) with $k = 1$, $m = 1$ and $n = 5$. Let the input premise be

cold = high
fever = mild
$\mu_<(cold, fever) = 0.7$
headache = high
$\mu_0(fever, headache) = 0.8$.

Let us define some of the relevant fuzzy sets:

severe = 0.8/0.8+1/0.9+1/1
acute = 0.8/0.9+1/1
high = 0.5/0.6+0.7/0.7+0.9/0.8+1/0.9+1/1
mild = 0.4/0.3+0.8/0.4+1/0.5+0.8/0.6+0.4/0.7.

Here we have represented the fuzzy set $A = \Sigma \mu_A(u)/u$ where u is a generic element of U, the universe of discourse of the fuzzy set A, and $\mu_A(u)$ is the membership function of A. Then $\tau_{11} = 1$, $\tau_{12} = 0.5$, $\tau_{13} = 0.7$, $\tau_{14} = 1$ and $\tau_{15} = 0.8$. The overall consistency of the input premise tuple is

$$\tau_1 = 1 \wedge 0.5 \wedge 0.7 \wedge 1 \wedge 0.8 = 0.5.$$

Then the conclusion that the patient has SINUSITIS is given by the fuzzy set:

$$\tau_1 \wedge acute = 0.5/0.9+0.5/1.$$

Comment 5.1: The above rule is extremely simple and not very accurate (medically). Its main purpose is just the illustration of the relevant concepts. More appropriate linguistic terms can be used to describe the symptoms and of course, we shall have to define appropriate fuzzy sets for the chosen set of linguistic descriptors [38]. Further we shall need to assign a linguistic label to the fuzzy set representing the conclusion. This is done through a process of *linguistic approximation* [35].

Comment 5.2: By using the temporal representation of symptoms developed in Section 4, we can calculate $\mu_<(cold, fever)$ and $\mu_0(fever, headache)$ required in the above rules. Our proposed temporal representation for symptoms enables us to manipulate symptoms easily and compute temporal relationships between symptoms which can be used in the rules of the expert system. It is also possible to have linguistic hedges in our temporal relations, e.g. if the rule in our example above was

IF [1]PATIENT HAS SEVERE COLD MUCH BEFORE HIGH FEVER, AND
...

then $\tau_{13} = 0.7^2 = 0.49$, where we have used the modification function

$$\mu_{much-before} = \int_{UiXUj} \mu^2_{before}(u_i, u_j)/(u_i, u_j).$$

The rules in the expert system are *fuzzy* rules, and hence have the additional advantage of producing a conclusion even when there is no exact match between the premises of the various rules and the input premise tuple. This is not possible in traditional expert systems where an exact match between the input premises and the premises of the rules is required. Thus these fuzzy rules are more general and more powerful than the crisp rules in a conventional expert system.

6 CONCLUSION

In this paper we have developed a model based on fuzzy set theory for temporal reasoning and demonstrated its applicability in the general context of fuzzy rules in expert systems. The proposed model allows a simple and natural representation of symptoms and efficient computation of the temporal relationships between complex symptoms. It has the disadvantage of the discrimination in the results being affected by the granularity of the chosen time intervals.

Table 3

COLD	FEVER	(COLD;FEVER)	HEADACHE	(FEVER;HEADACHE)	SINUSITIS
SEVERE	HIGH	BEFORE	SEVERE	OVERLAP	ACUTE

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87/44	Jonathan HAMILTON, Jacques-F. THISSE and Anita WESKAMP	**"Spatial discrimination: Bertrand vs. Cournot in a model of location choice"**, December 1987.
87/45	Karel COOL, David JEMISON and Ingemar DIERICKX	**"Business strategy, market structure and risk-return relationships: a causal interpretation"**, December 1987.
87/46	Ingemar DIERICKX and Karel COOL	**"Asset stock accumulation and sustainability of competitive advantage"**, December 1987.

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88/01	Michael LAWRENCE and Spyros MAKRIDAKIS	**"Factors affecting judgemental forecasts and confidence intervals"**, January 1988.
88/02	Spyros MAKRIDAKIS	**"Predicting recessions and other turning points"**, January 1988.
88/03	James TEBOUL	**"De-industrialize service for quality"**, January 1988.

88/04	Susan SCHNEIDER	**"National vs. corporate culture: implications for human resource management"**, January 1988.
88/05	Charles WYPLOSZ	**"The swinging dollar: is Europe out of step?"**, January 1988.
88/06	Reinhard ANGELMAR	**"Les conflits dans les canaux de distribution"**, January 1988.
88/07	Ingemar DIERICKX and Karel COOL	**"Competitive advantage: a resource based perspective"**, January 1988.
88/08	Reinhard ANGELMAR and Susan SCHNEIDER	**"Issues in the study of organizational cognition"**, February 1988.
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88/10	Bernard SINCLAIR-DESGAGNÉ	**"The robustness of some standard auction game forms"**, February 1988.
88/11	Bernard SINCLAIR-DESGAGNÉ	**"When stationary strategies are equilibrium bidding strategy: The single-crossing property"**, February 1988.
88/12	Spyros MAKRIDAKIS	**"Business firms and managers in the 21st century"**, February 1988
88/13	Manfred KETS DE VRIES	**"Alexithymia in organizational life: the organization man revisited"**, February 1988.
88/14	Alain NOEL	**"The interpretation of strategies: a study of the impact of CEOs on the corporation"**, March 1988.
88/15	Anil DEOLALIKAR and Lars-Hendrik RÖLLER	**"The production of and returns from industrial innovation: an econometric analysis for a developing country"**, December 1987.
88/16	Gabriel HAWAWINI	**"Market efficiency and equity pricing: international evidence and implications for global investing"**, March 1988.
88/17	Michael BURDA	**"Monopolistic competition, costs of adjustment and the behavior of European employment"**, September 1987.
88/18	Michael BURDA	**"Reflections on "Wait Unemployment" in Europe"**, November 1987, revised February 1988.
88/19	M.J. LAWRENCE and Spyros MAKRIDAKIS	**"Individual bias in judgements of confidence"**, March 1988.
88/20	Jean DERMINE, Damien NEVEN and J.F. THISSE	**"Portfolio selection by mutual funds, an equilibrium model"**, March 1988.
88/21	James TEBOUL	**"De-industrialize service for quality"**, March 1988 (88/03 Revised).
88/22	Lars-Hendrik RÖLLER	**"Proper Quadratic Functions with an Application to AT&T"**, May 1987 (Revised March 1988).
88/23	Sjur Didrik FLAM and Georges ZACCOUR	**"Equilibres de Nash-Cournot dans le marché européen du gaz: un cas où les solutions en boucle ouverte et en feedback coïncident"**, Mars 1988.
88/24	B. Espen ECKBO and Herwig LANGOHR	**"Information disclosure, means of payment, and takeover premia. Public and Private tender offers in France"**, July 1985, Sixth revision, April 1988.
88/25	Everette S. GARDNER and Spyros MAKRIDAKIS	**"The future of forecasting"**, April 1988.
88/26	Sjur Didrik FLAM and Georges ZACCOUR	**"Semi-competitive Cournot equilibrium in multistage oligopolies"**, April 1988.

88/27	Murugappa KRISHNAN Lars-Hendrik RÖLLER	**"Entry game with resalable capacity"**, April 1988.
88/28	Sumantra GHOSHAL and C. A. BARTLETT	**"The multinational corporation as a network: perspectives from interorganizational theory"**, May 1988.
88/29	Naresh K. MALHOTRA, Christian PINSON and Arun K. JAIN	**"Consumer cognitive complexity and the dimensionality of multidimensional scaling configurations"**, May 1988.
88/30	Catherine C. ECKEL and Theo VERMAELEN	**"The financial fallout from Chernobyl: risk perceptions and regulatory response"**, May 1988.
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88/32	Kasra FERDOWS and David SACKRIDER	**"International manufacturing: positioning plants for success"**, June 1988.
88/33	Mihkel M. TOMBAK	**"The importance of flexibility in manufacturing"**, June 1988.
88/34	Mihkel M. TOMBAK	**"Flexibility: an important dimension in manufacturing"**, June 1988.
88/35	Mihkel M. TOMBAK	**"A strategic analysis of investment in flexible manufacturing systems"**, July 1988.
88/36	Vikas TIBREWALA and Bruce BUCHANAN	**"A Predictive Test of the NBD Model that Controls for Non-stationarity"**, June 1988.
88/37	Murugappa KRISHNAN Lars-Hendrik RÖLLER	**"Regulating Price-Liability Competition To Improve Welfare"**, July 1988.
88/38	Manfred KETS DE VRIES	**"The Motivating Role of Envy : A Forgotten Factor in Management"**, April 88.
88/39	Manfred KETS DE VRIES	**"The Leader as Mirror : Clinical Reflections"**, July 1988.
88/40	Josef LAKONISHOK and Theo VERMAELEN	**"Anomalous price behavior around repurchase tender offers"**, August 1988.
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88/42	Paul EVANS	**"Organizational development in the transnational enterprise"**, June 1988.
88/43	B. SINCLAIR-DESGAGNÉ	**"Group decision support systems implement Bayesian rationality"**, September 1988.
88/44	Essam MAHMOUD and Spyros MAKRIDAKIS	**"The state of the art and future directions in combining forecasts"**, September 1988.
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88/46	Yves DOZ and Amy SHUEN	**"From intent to outcome: a process framework for partnerships"**, August 1988.
88/47	Alain BULTEZ, Els GIJSBRECHTS, Philippe NAERT and Piet VANDEN ABEELE	**"Asymmetric cannibalism between substitute items listed by retailers"**, September 1988.
88/48	Michael BURDA	**"Reflections on 'Wait unemployment' in Europe, II"**, April 1988 revised September 1988.
88/49	Nathalie DIERKENS	**"Information asymmetry and equity issues"**, September 1988.
88/50	Rob WEITZ and Arnoud DE MEYER	**"Managing expert systems: from inception through updating"**, October 1987.
88/51	Rob WEITZ	**"Technology, work, and the organization: the impact of expert systems"**, July 1988.

88/52	Susan SCHNEIDER and Reinhard ANGELMAR	**"Cognition and organizational analysis: who's minding the store?"**, September 1988.
88/53	Manfred KETS DE VRIES	**"Whatever happened to the philosopher-king: the leader's addiction to power,** September 1988.
88/54	Lars-Hendrik RÖLLER and Mihkel M. TOMBAK	**"Strategic choice of flexible production technologies and welfare implications"**, October 1988
88/55	Peter BOSSAERTS and Pierre HILLION	**"Method of moments tests of contingent claims asset pricing models"**, October 1988.
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88/63	Fernando NASCIMENTO and Wilfried R. VANHONACKER	**"Strategic pricing of differentiated consumer durables in a dynamic duopoly: a numerical analysis"**, October 1988.
88/64	Kasra FERDOWS	**"Charting strategic roles for international factories"**, December 1988.
88/65	Arnoud DE MEYER and Kasra FERDOWS	**"Quality up, technology down"**, October 1988
88/66	Nathalie DIERKENS	**"A discussion of exact measures of information assymetry: the example of Myers and Majluf model or the importance of the asset structure of the firm"**, December 1988.
88/67	Paul S. ADLER and Kasra FERDOWS	**"The chief technology officer"**, December 1988.

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89/01	Joyce K. BYRER and Tawfik JELASSI	**"The impact of language theories on DSS dialog"**, January 1989.
89/02	Louis A. LE BLANC and Tawfik JELASSI	**"DSS software selection: a multiple criteria decision methodology"**, January 1989.
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89/09	Damien NEVEN, Carmen MATUTES and Marcel CORSTJENS	**"Brand proliferation and entry deterrence"**, February 1989.
89/10	Nathalie DIERKENS, Bruno GERARD and Pierre HILLION	**"A market based approach to the valuation of the assets in place and the growth opportunities of the firm"**, December 1988.
89/11	Manfred KETS DE VRIES and Alain NOEL	**"Understanding the leader-strategy interface: application of the strategic relationship interview method"**, February 1989.
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89/14	Reinhard ANGELMAR	**"Product innovation: a tool for competitive advantage"**, March 1989.
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89/20	Wilfried VANHONACKER and Russell WINER	**"A rational random behavior model of choice"**, Revised March 1989.
89/21	Arnoud de MEYER and Kasra FERDOWS	**"Influence of manufacturing improvement programmes on performance"**, April 1989.
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89/32	Peter HAUG and Tawfik JELASSI	**"Application and evaluation of a multi-criteria decision support system for the dynamic selection of U.S. manufacturing locations"**, May 1989.
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89/40	Balaji CHAKRAVARTHY	**"Management systems for innovation and productivity"**, June 1989.
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89/43	Michael BURDA	**"A note on firing costs and severance benefits in equilibrium unemployment"**, June 1989.
89/44	Balaji CHAKRAVARTHY and Peter LORANGE	**"Strategic adaptation in multi-business firms"**, June 1989.
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89/46	Marcel CORSTJENS, Carmen MATUTES and Damien NEVEN	**"Entry Encouragement"**, July 1989.
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89/53	Spyros MAKRIDAKIS	**"Why combining works?"**, July 1989.
89/54	S. BALAKRISHNAN and Mitchell KOZA	**"Organisation costs and a theory of joint ventures"**, September 1989.

89/55	H. SCHUTTE	**"Euro-Japanese cooperation in information technology"**, September 1989.
89/56	Wilfried VANHONACKER and Lydia PRICE	**"On the practical usefulness of meta-analysis results"**, September 1989.
89/57	Taekwon KIM, Lars-Hendrik RÖLLER and Mihkel TOMBAK	**"Market growth and the diffusion of multiproduct technologies"**, September 1989.
89/58 (EP,TM)	Lars-Hendrik RÖLLER and Mihkel TOMBAK	**"Strategic aspects of flexible production technologies"**, October 1989.
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89/67 (FIN)	Peter BOSSAERTS and Pierre HILLION	**"Market microstructure effects of government intervention in the foreign exchange market"**, December 1989.

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90/01 TM/EP/AC	B. SINCLAIR-DESGAGNÉ	**"Unavoidable Mechanisms"**, January 1990.
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90/24 FIN/EP	Lars Tyge NIELSEN	**"Positive Prices in CAPM"**, January 1990.
90/25 FIN/EP	Lars Tyge NIELSEN	**"Existence of Equilibrium in CAPM"**, January 1990.
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90/27 TM	Abbas FOROUGHI and Tawfik JELASSI	**"NSS Solutions to Major Negotiation Stumbling Blocks"**, February 1990.
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90/29 FIN/AC	Nathalie DIERKENS	**"A Discussion of Correct Measures of Information Asymmetry"**, January 1990.
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90/31 MKT/EP	David GAUTSCHI and Roger BETANCOURT	**"What Determines U.S. Retail Margins?"**, February 1990.
90/32 SM	Srinivasan BALAK- RISHNAN and Mitchell KOZA	**"Information Asymmetry, Adverse Selection and Joint-Ventures: Theory and Evidence"**, Revised, January 1990.
90/33 OB	Caren SIEHL, David BOWEN and Christine PEARSON	**"The Role of Rites of Integration in Service Delivery"**, March 1990.

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90/35 EP	Jae Won PARK	**"Changing Uncertainty and the Time-Varying Risk Premia in the Term Structure of Nominal Interest Rates"**, December 1988, Revised March 1990.
90/36 TM	Arnoud DE MEYER	**"An Empirical Investigation of Manufacturing Strategies in European Industry"**, April 1990.
90/37 TM/OB/SM	William CATS-BARIL	**"Executive Information Systems: Developing an Approach to Open the Possibles"**, April 1990.
90/38 MKT	Wilfried VANHONACKER	**"Managerial Decision Behaviour and the Estimation of Dynamic Sales Response Models"**, (Revised February 1990).
90/39 TM	Louis LE BLANC and Tawfik JELASSI	**"An Evaluation and Selection Methodology for Expert System Shells"**, May 1990.
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90/48 EP	Jae WON PARK	**"The Information in the Term Structure of Interest Rates: Out-of-Sample Forecasting Performance"**, June 1990.
90/49 TM	Soumitra DUTTA	**"Approximate Reasoning by Analogy to Answer Null Queries"**, June 1990.
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90/57 FIN/EP/ TM	Lars Tyge NIELSEN	Common Knowledge of a Multivariate Aggregate Statistic", July 1990
90/58 FIN/EP/TM	Lars Tyge NIELSEN	"Common Knowledge of Price and Expected Cost in an Oligopolistic Market", August 1990
90/59 FIN	Jean DERMINE and Lars-Hendrik RÖLLER	"Economies of Scale and Scope in the French Mutual Funds (SICAV) Industry", August 1990
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90/65 EP	Charles WYPLOSZ	"A Note on the Real Exchange Rate Effect of German Unification", August 1990
90/66 TM/SE/FIN	Soumitra DUTTA and Piero BONISSONE	"Computer Support for Strategic and Tactical Planning in Mergers and Acquisitions", September 1990
90/67 TM/SE/FIN	Soumitra DUTTA and Piero BONISSONE	"Integrating Prior Cases and Expert Knowledge In a Mergers and Acquisitions Reasoning System", September 1990
90/68 TM/SE	Soumitra DUTTA	"A Framework and Methodology for Enhancing the Business Impact of Artificial Intelligence Applications", September 1990