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Analysis of Process Models: A Fuzzy Logic Approach

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Process modelling tools, such as the Integrated DEFinition (IDEF) methodology, allow for a systematic and a well-defined representation of processes, e.g. manufacturing, product development, and business. The most frequently recognised shortcoming of process modelling is the lack of analysis tools. Owing to the qualitative and static nature of models, mathematical techniques are difficult to apply. To make the process modelling methodologies more attractive, formal techniques for analysis of process models are required. In this paper, an analysis approach for process models, based on fuzzy logic and approximate rule-based reasoning, is presented. Possibility distributions are used to represent uncertain and incomplete information of process variables. An approximate rule based reasoning approach is developed for quantitative analysis of process models. The effectiveness of the approach is illustrated with an industrial example. The architecture of an expert system for the quantitative analysis of process models is also outlined.

Keywords: Approximate reasoning; Fuzzy logic; Process analysis; Process models; Quantitative analysis

1. Introduction

A process model includes a set of activities arranged in a specific order, with clearly identified inputs and outputs. The output of the process may be either a product or a service [1]. Each activity in a process takes an input and transforms it into an output with some value to a customer. Ideally, any transformation occurring in the process should add value to the input and create an output that is useful to a downstream recipient.

An important advantage of process representation over traditional functional approaches is in its structure. A thorough understanding of functions, data, and resources is essential in modelling processes. A model of the process system can provide this understanding without disturbing the actual environment. For example, in manufacturing, models can be used to analyse the ability of the manufacturing system to respond to market changes. This enables rapid and accurate reconfiguration when new products are demanded.

Several process modelling methodologies are currently available and used by various companies, i.e. computer integrated manufacturing – open systems architecture (CIM-OSA) methodology [2,3], object-oriented modelling methodology for manufacturing [4], and Petri nets [5]. Based on some of the above methodologies, a number of process modelling tools have been developed, e.g. ARIS (Germany), FirstStep (Canada), PrimeObjects (Italy), and TEMAS (Switzerland).

An important attribute of a modelling technique is extendibility, as a universal modelling technique is not available. Of all methodologies discussed above, the Integrated DEFinition (IDEF) methodology (discussed in the next section) is perhaps the simplest to use and the easiest to extend. It has been broadly accepted by companies to model diverse processes [6].

The IDEF3 (Integrated DEFinition 3) methodology offers several important characteristics for successful process representation:

1. Process description in the form of activities.
2. Structure of the underlying process.
3. Flow of objects and their relationships [7].

In spite of these advantages, IDEF3 methodology is static and qualitative, which is a drawback to the analysis of processes [8]. Activities in a model are at a relatively high level of abstraction, making it difficult to associate exact quantitative data for the process variable of interest.

In this paper, a new analysis approach for process models is presented. Membership functions of fuzzy sets are used to represent uncertain and incomplete information of process variables. An approximate rule-based reasoning approach is developed for quantitative analysis of process models. A framework of an expert system for quantitative analysis of IDEF3 process models is also outlined.

1.1 IDEF3 Methodology

IDEF3 methodology has been extensively used for modelling manufacturing processes. The essence of IDEF3 methodology

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is its ability to describe activities and their relationships at various levels of detail. An initial model includes parent activities that are decomposed into lower-level activities. The IDEF3 methodology syntax includes the semantics of first-order logic and graphical syntax [6]. The relationship between activities in IDEF3 is modelled with three types of links: precedence; object flow; and relational. The precedence and object-flow links express the simple temporal precedence between activities. The relational links highlight the existence of a relationship between activities. The logic of branching within a process is modelled using *AND* (&), *OR* (O), and *exclusive OR* (X) junction boxes. Multiple-process paths corresponding to converging and diverging paths (scenarios) are referred to as *fan-ins* or *fan-outs*. The relative timing of fan-ins and fan-outs can be *synchronous* or *asynchronous*. For details of the IDEF3 process capture methods, see Menzel et al. [9].

In the recent years, a number of papers have been published on analysis of IDEF models. Belhe and Kusiak [10] developed a procedure to generate alternative precedence networks from an IDEF3 network of design activities. They proposed an algorithm determining a lower bound for the completion time for a hierarchically structured network, by making use of an existing reduction procedure. Ang and Gay [11] examined the adequacy of IDEF0 methodology and suggested a number of modifications and enhancements in order to improve its descriptive power for project risk assessment. Kusiak and Larson [12] integrated techniques for analysis of system reliability with an IDEF3 model. Kusiak and Zakarian [13,14] developed a fault-tree based methodology for reliability evaluation and risk assessment of the parent activities of an IDEF3 model. The system reliability evaluation techniques were extended for analysis of IDEF3 models. The process-analysis approaches presented in the above papers assume that the exact quantitative information of IDEF process variables, such as the reliability [12] and processing time of each activity [10] are available. However, in practice, the activities in a process model might be at a high level of abstraction. Typically, process variables representing the activities are not defined and contain uncertain and incomplete information. As an example, consider the IDEF3 model of the film deposition process shown in Fig. 1. Properties of films typically depend on the deposition technique and conditions. A major consideration in selecting a deposition technique is the desired circuit thickness of films. Smaller circuit thickness provides better film resolution and accuracy. Usually, the choice of deposition method is made after the material is selected. Once the material is selected, the film can be manufactured, for example, either by using the conventional thin-film technology, i.e. using activities 1, 2, 4, 8 in Fig. 1, or by metallo-organic-deposition (MOD) film technology, i.e. using activities 1, 3, 5, 6, 7, 8. The MOD film-deposition process consists of screen printing of a continuous layer of gold-based metallo-organic material into a substrate. After the printed parts are dried for 10–20 min at 125°C, the resulting gold film can be built up to the desired thickness by electroplating or by screen printing a layer of fritless gold material. For the latter, the desired circuit patterns are formed using photolithography techniques, e.g. subtractive etching [15,16]. The conventional thin-film technology process consists of sputtering and screen printing operations. To achieve the desired film thickness, typically, several experiments are carried out for different input parameters, to determine optimal deposition conditions.

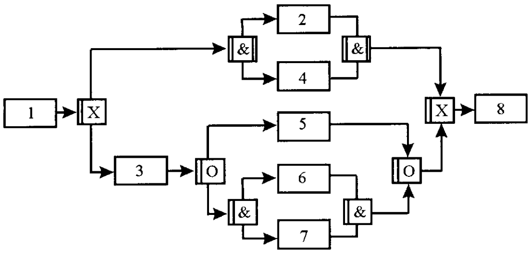

Fig. 1. IDEF3 model of the film deposition process. 1, select material; 2, perform sputtering; 3, perform screen printing; 4, perform pattern plating; 5, obtain final layer by electroplating; 6, obtain final layer by adding fritless gold; 7, perform subtractive etching; 8, form a circuit.

For the film-deposition process shown in Fig. 1, assume that the analyst wants to perform an output analysis of the process of manufacture a circuit. With the quantitative information of process variables available, a simulation technique can be used to perform the analysis, or, knowing the reliability and the processing time of each activity involved in the process, the approaches presented in [12] and [10] can determine the reliability of the process, and the lower bound of the duration of the process, respectively. However, most of the process modelling methodologies, including IDEF, are based on informal notation and lack quantitative information. The process model in Fig. 1 represents an ordered sequence of events, tasks, and activities with clearly identified inputs and outputs of the film-deposition process. However, to perform output analysis of the process of manufacturing a circuit, process variables must be identified and quantified. The identification of process variables may be accomplished by examining the process itself. For example, if it is assumed that the output of the process is the final thickness of the circuit, then the remaining process variables that contribute to the process output variable may be identified and defined (see Table 1). To perform quantitative analysis of process models in this paper, an approach based on fuzzy logic and rule-based reasoning is presented. The

Table 1. IDEF3 model activity names, process variables, symbols, and units.

Number	Activity name	Process variable	Symbol	Unit
1	Select material	Thermal conductivity	TC	cal s^{-1} cm^{-1}
2	Perform sputtering	Sputtering yield	SY	atoms/ion
3	Perform screen printing	Surface roughness	SR	mil
4	Perform pattern plating	Plating density	PD	g cm^{-3}
5	Obtain final layer by electroplating	Electroplating density	ED	g cm^{-3}
6	Obtain final layer by adding fritless gold	Layer density	LD	g cm^{-3}
7	Perform subtractive etching	Etched film average thickness	EAT	Å (Angstrom)
8	Form a circuit	Final thickness of circuit	CT	Å

approach integrates fuzzy-rule-based reasoning with IDEF3 methodology for quantitative analysis of process models with imperfect knowledge.

2. Fuzzy Sets and Fuzzy Logic

The theory of fuzzy sets [17] deals with a subset of the universe of discourse, where the transition between full membership and non-membership is gradual rather than abrupt. For standard sets, also known as crisp or non-fuzzy sets, if A is a crisp subset of X, the function

$$\mu_A(x) = \begin{cases} 1 & \text{for } x \in A \\ 0 & \text{for } x \notin A \end{cases}$$

is called the characteristic function of A. The grade here has two values: 0 and 1, if x is an element of A its value is 1; otherwise it is 0.

In fuzzy-set theory an object may belong only partially. Therefore, the grade in a fuzzy set can be anything from zero to one, and its membership function is $\mu_A(x)$: $X \rightarrow [0,1]$ with the grades 1 and 0 representing, respectively, full membership and non-membership in a fuzzy set.

In traditional rule-based reasoning, rules are represented in the form of premise–consequent (IF-THEN) structures. When new data are encountered, they are matched with the premise clause of each rule, and the rules for which the premise is exactly satisfied are fired, establishing the consequent clauses. This reasoning approach assumes that all the process facts are known with certainty. This constraint which is rarely satisfied in real process modelling and analysis applications. Uncertainty in the process, i.e. uncertainty in the process variables, uncertainty in the facts, and uncertainty in the rules describing causal relations among facts, is almost always present.

The concepts of fuzzy sets and fuzzy logic have been widely used in fuzzy modelling of systems. Fuzzy modelling is based on the fact that a precise mathematical model of a system is difficult to obtain and so describes the system with fuzzy quantities. Fuzzy quantities are expressed in terms of fuzzy numbers or linguistic labels of fuzzy sets. A fuzzy logic consists of IF-THEN fuzzy rules, where the IF portion of the rule includes the premise part and THEN portion, the consequence part. The premises and consequences of fuzzy rules contain linguistic variables. An inference procedure of fuzzy logic takes the fuzzy sets representing the rules and the facts and produces a resultant fuzzy set, over the domain of discourse of the consequent. Therefore, fuzzy rules are like traditional IF-THEN rules, except for two important differences [18]:

1. The premises and conclusions of fuzzy rules contain linguistic variables.
2. The inference procedure with fuzzy rules is different from that of conventional IF/THEN rules.

To present an approximate reasoning approach for the process modelling, the operations of fuzzy intersection, union, and complement are introduced next.

Fuzzy Intersection (t-norm): The intersection of fuzzy sets A and B is a function of the form $\mu_{A \cap B}(x)$: $[0,1] \times [0,1] \rightarrow [0,1]$ and is obtained from (1) by taking the minimum of the degrees of membership of the elements in A and B (see Fig. 2(*a*)). The intersection is analogous to the logical AND (conjunction), that generally demands simultaneous satisfaction of the operands A and B.

$$\mu_{A \cap B}(x) = \mu_A(x) \bigvee \mu_B(x) \quad \text{where } (\bigvee = \min) \tag{1}$$

Fuzzy Union (t-conorm): The union of fuzzy sets A and B is a function of the form $\mu_{A \cup B}(x)$: $[0,1] \times [0,1] \rightarrow [0,1]$ and is obtained from (2) by taking the maximum of the degrees of membership of the elements in A and B (see Fig. 2(*b*)). The union is analogous to the logical OR (conjunction), in which some interchangeability between the two arguments of the statement "*A* or *B*" is assumed.

$$\mu_{A \cup B}(x) = \mu_A(x) \bigwedge \mu_B(x) \quad \text{where } (\bigwedge = \max) \tag{2}$$

Fuzzy Complement: The complement of fuzzy set A is a function of the form $\mu_{\bar{A}}(x)$: $[0,1] \rightarrow [0,1]$ and is obtained from (3) by subtracting from 1, the degree of membership of the various elements in the domain (see Fig. 2(*c*)).

$$\mu_{\bar{A}}(x) = 1 - \mu_a(x) \tag{3}$$

Equations (1) to (3) are simple extensions of classical set theory operations and are known as Zadeh's De Morgan triple. Some other extensions are also possible and are summarised in Table 2 [19].

3. Fuzzy Reasoning with IDEF3 Models

Fuzzy approximate reasoning is based on possibility distribution. Possibility distribution is a fuzzy set with a limit on the values that may be assigned to a variable [20]. Possibility distributions can be used to describe uncertain and incomplete information about linguistic variables of an IDEF3 model. For each activity in a process model there are two types of linguistic variables: input and output. Fuzzy logic, i.e. IF-THEN fuzzy rules, can be used to model the relationships between input and output variables of an IDEF3 process model. In these rules, input variables of an IDEF3 process model appear only in the premise parts (i.e. IF parts) of fuzzy rules, while the output variables can be found in the consequent parts (i.e. THEN parts). Consider a fuzzy reasoning problem of the serial activities "select material" and "perform screen printing" in the IDEF3 process model in Fig. 1. Assume the following two fuzzy rules are given:

Rule 1. IF thermal conductivity is low THEN surface roughness is normal.
Rule 2. IF thermal conductivity is high THEN surface roughness is about normal.

Linguistic variables "high", "low", "normal", and "about normal" can be modelled with possibility distributions over the appropriate domain. For example, high thermal conductivity may be defined by a fuzzy set as being greater than $0.16 \text{ cal s}^{-1} \text{ cm}^{-1}$, "normal" surface roughness as being less than 1.3 mil and greater than 0.9 mil (see Fig. 3). If the proposition is:

P1. Thermal conductivity is high.

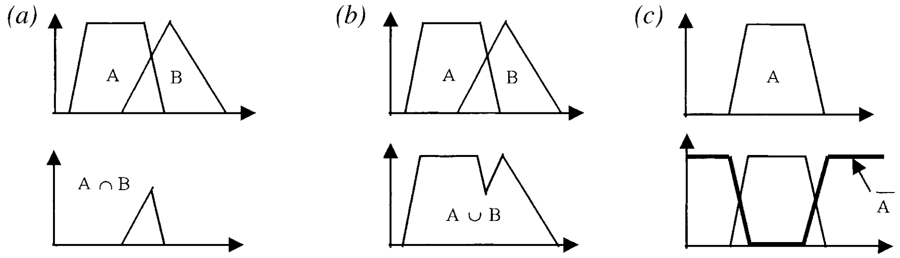

Fig. 2. Operations of fuzzy set: (*a*) intersection, (*b*) union, and (*c*) complement.

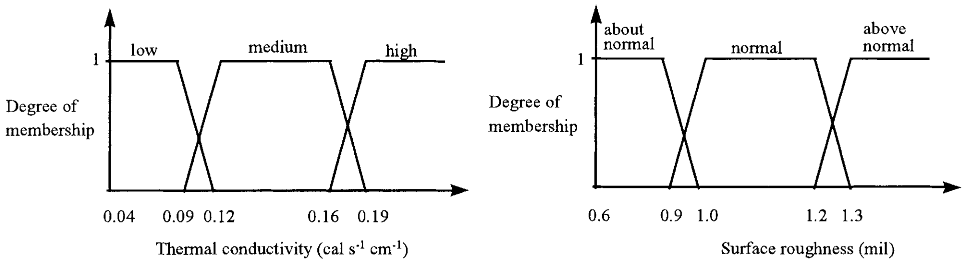

Fig. 3. Membership functions representing thermal conductivity and surface roughness.

Table 2. Fuzzy logic operators.

	t-norms	*t*-conorms
Logical	$T(a \cap b) = \min(a,b)$	$C(a \cup b) = \min(a,b)$
Algebraic	$T(a \cap b) = ab$	$C(a \cup b) = a + b - ab$
Bounded	$T(a \cap b) = \max[0, a + b - 1]$	$C(a \cup b) = \min[1, a + b]$
Drastic	$T(a \cap b) = \begin{cases} a & \text{when } b = 1 \\ b & \text{when } a = 1 \\ 0 & \text{otherwise} \end{cases}$	$C(a \cup b) = \begin{cases} a & \text{when } b = 0 \\ b & \text{when } a = 0 \\ 1 & \text{otherwise} \end{cases}$

then, from Rule 1, it may be concluded that the surface roughness is "about normal". This formulation presents a problem when proposition P1 does not exactly match at least one premise in Rules 1 or 2. For example, assume the new proposition is

P2. Thermal conductivity is medium

Then neither premise in Rules 1 and 2 directly matches proposition P2 and the approach discussed above cannot be used to compute the output value of surface roughness. Although there is no direct match between the premises of two fuzzy Rules 1 and 2 and proposition P2, a partial match with each rule does exist. From this partial match the output value of surface roughness can be computed using the following three steps [19,21]:

Step 1. Compute the intersection of P2 with each of the premise of Rules 1 and 2.

Step 2. Determine the contribution of each of the fuzzy Rules 1 and 2 to the output value of surface roughness by taking the portion of the output fuzzy distributions.

Step 3. Take the union of the contributions of the conclusions of each rule to obtain the final value of surface roughness.

The result of these three steps is a possibility distribution (fuzzy set) describing the output value of surface roughness. To obtain a crisp number for surface roughness the output fuzzy set is "defuzzified". Several methods of defuzzification have been proposed in the literature, see, for example, Tsukamoto [22] and Berenji [23]. In this paper, the centre of mass defuzzification method is used. According to this method, coordinate x of the centre of mass of the output distribution is the output value of surface roughness.

The rule-based-reasoning scheme described above may be used for approximate reasoning with serial activities of an IDEF3 model connected with precedence and object flow links. An approximate reasoning approach for parallel activities of an IDEF3 model is discussed next.

3.1 Fuzzy Reasoning with Parallel Activities of an IDEF3 Model

Fuzzy logic may also be used for modelling the relationships between parallel activities in an IDEF3 model connected with AND and OR logical links. Here, the IF portion of each fuzzy rule should include multiple premises. In fact, the number of premises in each fuzzy rule should be equal to the number of activities following an AND or OR logical link. Furthermore, a logical connector describing the relationship between parallel activities in an IDEF3 model also identifies the logical relationships between multiple premises in fuzzy rules. For example, consider the fuzzy reasoning problem of parallel activities "perform sputtering" and " perform pattern plating" (connected with an AND logical link) in the film deposition process in Fig. 1. The IF portion of a fuzzy rule representing the relationships between these activities must include two premises connected with an AND logical link. To illustrate the fuzzy reasoning of parallel activities of an IDEF3 model, following an AND logical link, assume Rules 3 and 4 (presented below) describe the relationships between process variables, sputtering yield, plating density, and final thickness of circuit.

Rule 3. IF sputtering yield is high AND plating density is low THEN final thickness of circuit is small.
Rule 4. IF sputtering yield is medium AND plating density is high THEN final thickness of circuit is medium.

Also assume propositions P3 and P4 (presented below) are given.

P3. Sputtering yield is *l*.
P4. Plating density is medium.

Then one may use the *t*-norms and the three steps described in Section 3 to compute the final thickness of a circuit (see Fig. 4). If it is assumed that the parallel activities "perform sputtering" and "perform pattern plating" in an IDEF3 model connected with an OR logical link, then the structure of Rules 3 and 4 will be as follows:

Rule 5. IF sputtering yield is high OR plating density is low THEN final thickness of circuit is small.
Rule 6. IF sputtering yield is medium OR plating density is high THEN final thickness of circuit is medium.

and for propositions P3 and P4 the final thickness of the circuit may be calculated using *t*-conorms and the steps described in Section 3 (see Fig. 5).

An exclusive OR connector in an IDEF3 model represents a "conditional branch" in a process, i.e. a point where the process can flow in only one of several ways. Therefore, an exclusive OR logical link represents a decision point in the process, and its application is discussed in the next section with an industrial example.

4. Industrial Application

The IDEF3 model of the film deposition process presented in Fig. 1 is used to illustrate the approach discussed in [24]. The example is taken from an industrial company. The process is a small component of the manufacturing function at the company. At the first level of abstraction, eight activities are included. The first activity in the model is to select the material of a circuit. Once the material has been selected, the circuit can be formed either by using the existing conventional thin-film technology or by metallo-organic-deposition (MOD) film technology (but not both). This is indicated by the exclusive OR junction in Fig. 1. If thin-film technology is selected, the sputtering and pattern plating operations are performed. If MOD film technology is selected, then the screen printing activity is performed and the final layer is obtained by electroplating or by adding fritless gold and performing subtractive etching. These relationships are reflected by the OR and AND junction, respectively.

Once the process model of the film deposition process is constructed and the relationships between activities are determined, a membership function for each process variable is build. Figure 6 shows the membership functions representing thin-film technology process variables. In this example, trapezoidal and triangular membership functions are used. The quantitative information for membership functions in Fig. 6 was obtained from process engineers and the manufacturing process knowledge base. It has to be emphasised that the membership functions may take various shapes, not necessarily trapezoidal or triangular. Next, quantitative analysis of the film deposition process may be performed. In this research, MATLAB software is used to perform the analysis. For the thin-film technology

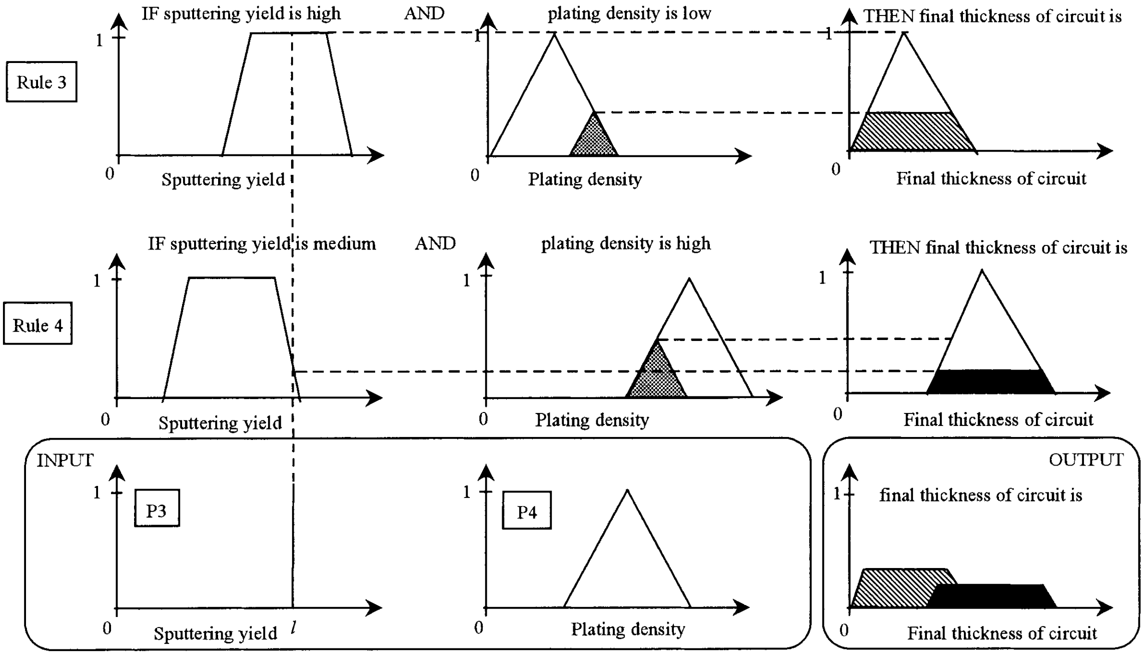

Fig. 4. Fuzzy inference of parallel activities modelled with an AND logical link.

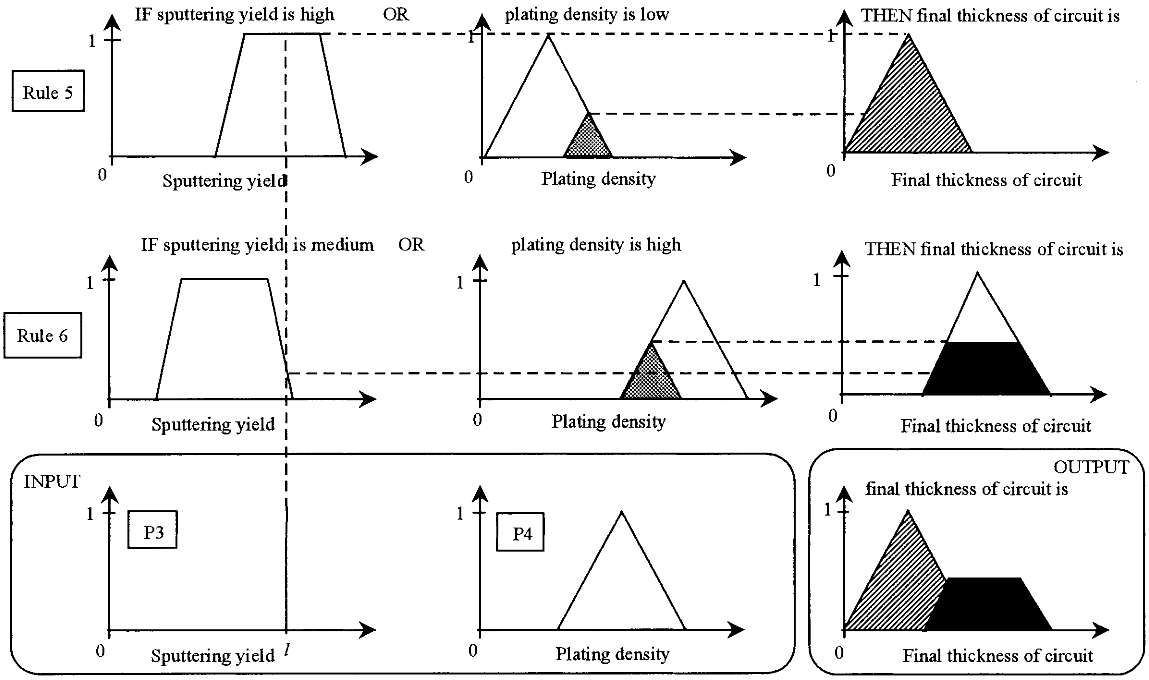

Fig. 5. Fuzzy inference of parallel activities modelled with an OR logical link.

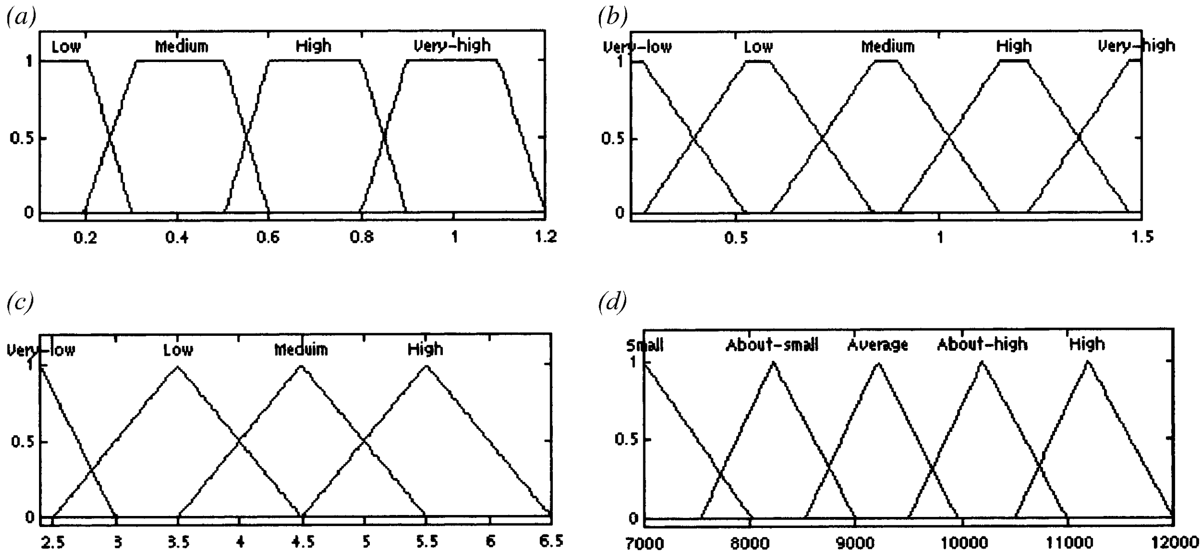

Fig. 6. Membership functions representing IDEF3 process variables: (*a*) thermal conductivity, (*b*) sputtering yield, (*c*) plating density, and (*d*) final circuit thickness.

process three different sets of rules describing the relationships between activities 1 and 2 (Fig. 7(*a*)), 1 and 4 (Fig. 7(*b*)), and 2, 4 and 8 (Fig. 7(*c*)) are constructed. It should be noted that the rules describing relationships between activities 1 and 2, and 1 and 4 may be combined into rule set 4 (see Fig. 8). The latter decreases the approximate reasoning computational efforts.

Figure 9 illustrates the fuzzy reasoning computations of the thin-film deposition process. The analysis show that when TC = 0.879 cal s^{-1} cm^{-1} from Rule set 1, the sputtering yield (SY) is 0.479 atoms/ion (see Fig. 9(*a*)), and, from Rule set 2, the plating density (PD) is 5.35 g cm^{-3} (see Fig. 9(*b*)). Once the values of SY and PD are obtained, Rule set 3 and the approximate reasoning approach described in Fig. 4 may be used to determine that the circuit thickness (CT) of the thin film is 9100Å (see Fig. 9(*c*)). Table 3 presents the approximate reasoning computational results for different initial values of TC. For example, the computations in Table 3 show that when TC = 0.540 cal s^{-1} cm^{-1}, the circuit thickness is 10 900Å and 9800Å for the MOD and thin-film technology process, respect-

(a)

Rule set 1
1. IF (TC is Low) THEN (SY is Medium)
2. IF (TC is High) THEN (SY is Very-low)
3. IF (TC is Very-high) THEN (SY is Low)

(b)

Rule set 2
1. IF (TC is High) THEN (PD is Medium)
2. IF (TC is Low) THEN (PD is Very-low)
3. IF (TC is Very-high) THEN (PD is High)

(c)

Rule set 3
1. IF (SY is Low) AND (PD is High) THEN (CT is Average)
2. IF (SY is Medium) AND (PD is Low) THEN (CT is Small)
3. IF (SY is Very-high) AND (PD is High) THEN (CT is High)
4. IF (SY is Very-high) AND (PD is Low) THEN (CT is High)
5. IF (SY is Very-low) AND (PD is Medium) THEN (CT is About-high)

Fig. 7. Fuzzy rules of the industrial example.

Rule set 4
1. IF (TC is High) THEN (PD is Medium) and (SY is Very-low)
2. IF (TC is Low) THEN (PD is Very-low) and (SY is Medium)
3. IF (TC is Very-high) THEN (PD is High) and (SY is Low)

Fig. 8. Combined rule sets 1 and 2.

Table 3. Rule-based reasoning computational results for the industrial example.

Activity	Process variable							
	1	2	3	4	5	6	7	8
Symbol/ units	TC cal s^{-1} cm^{-1}	SY atoms/ ion	SR mil	PD g cm^{-1}	ED g cm^{-1}	LD g cm^{-1}	EAT Å	CT Å
Thin-film technology	0.879	0.479		5.35				9100
	0.234	0.769		2.40				9500
	0.540	0.240		3.92				9800
MOD film technology	0.879		0.20		1.56	3.57	125	10 200
	0.234		0.63		1.00	2.40	432	8050
	0.540		0.80		2.11	3.99	271	10 900

ively. The analysis also shows that in order to achieve a thickness 8050Å for a circuit using MOD film technology, TC = 0.234 cal s^{-1} cm^{-1} is required. The values of the remaining process variables SY, PD, SR, ED, LD, and EAT are calculated using the approximate reasoning approach developed in Section 3.

The reasoning strategy presented in this paper may be used for decision making by process engineers. The exclusive OR logical connectors in the IDEF3 model represent the decision points. The model in Fig. 1 contains one decision point following activity 1. Assume that a circuit thickness of at least 9400Å is required in the film deposition process. Once the material is selected and the value of thermal conductivity TC = 0.234 cal s^{-1} cm^{-1} is determined, the process analyst should decide between the two diverging paths (scenarios) following the decision point, i.e. the exclusive OR junction (see Fig. 1). Using the approximate reasoning strategy, the analyst may identify the scenario, corresponding to the thin-film technology, that yields the desired film thickness of 9500Å. When the required circuit thickness is between 8000Å and 9600Å then for given TC = 0.234 cal s^{-1} cm^{-1} at the decision point, there is a choice between the two diverging process paths. Here, a path may be selected based on the desired values of the other process variables.

5. Expert System for Analysis of Process Models

The procedure described in this paper provides the basis of an expert system for quantitative analysis of process models. The expert system consists of four elements:

1. Fuzzy membership function knowledge base.
2. Fuzzy production rule knowledge base.
3. Inference engine.
4. Defuzzifier.

The overall system architecture is presented in Fig. 10. The expert system accepts process graphical input in the form of an IDEF3 block diagram and using the data dictionary (which contains information about all activities, process variables and logical connectors of the model) builds membership functions of process variables and creates templates for fuzzy rules. Membership functions represent graphically uncertain and incomplete information of process variables, which makes it possible to transfer it into a knowledge-base system.

Fuzzy IF-THEN rules expressing a fuzzy implication relationship between fuzzy sets of the premise and fuzzy sets of the conclusion are also represented with the knowledge base. An inference engine is the part of an expert system that contains the general problem-solving knowledge. This allows the analyst to evaluate the outcome of the process by applying membership-function knowledge and fuzzy-rule knowledge to the solution of an actual problem. Furthermore, if a specific outcome from the process model is desired, then the inference engine may search the fuzzy rules specified for each activity that will lead to the desired process output. In other words the expert system in Fig. 10 allows forward and backward reasoning to be performed with an IDEF3 model.

There are several advantages of representing knowledge with a fuzzy-rule base. For example, system/process engineers can modify a few rules without reconstructing the entire knowledge-base system, or new rules (knowledge) can be added to the system without worrying about how they will fit in.

6. Conclusion

The IDEF3 methodology lends itself to the representation of manufacturing, product development, and business processes.

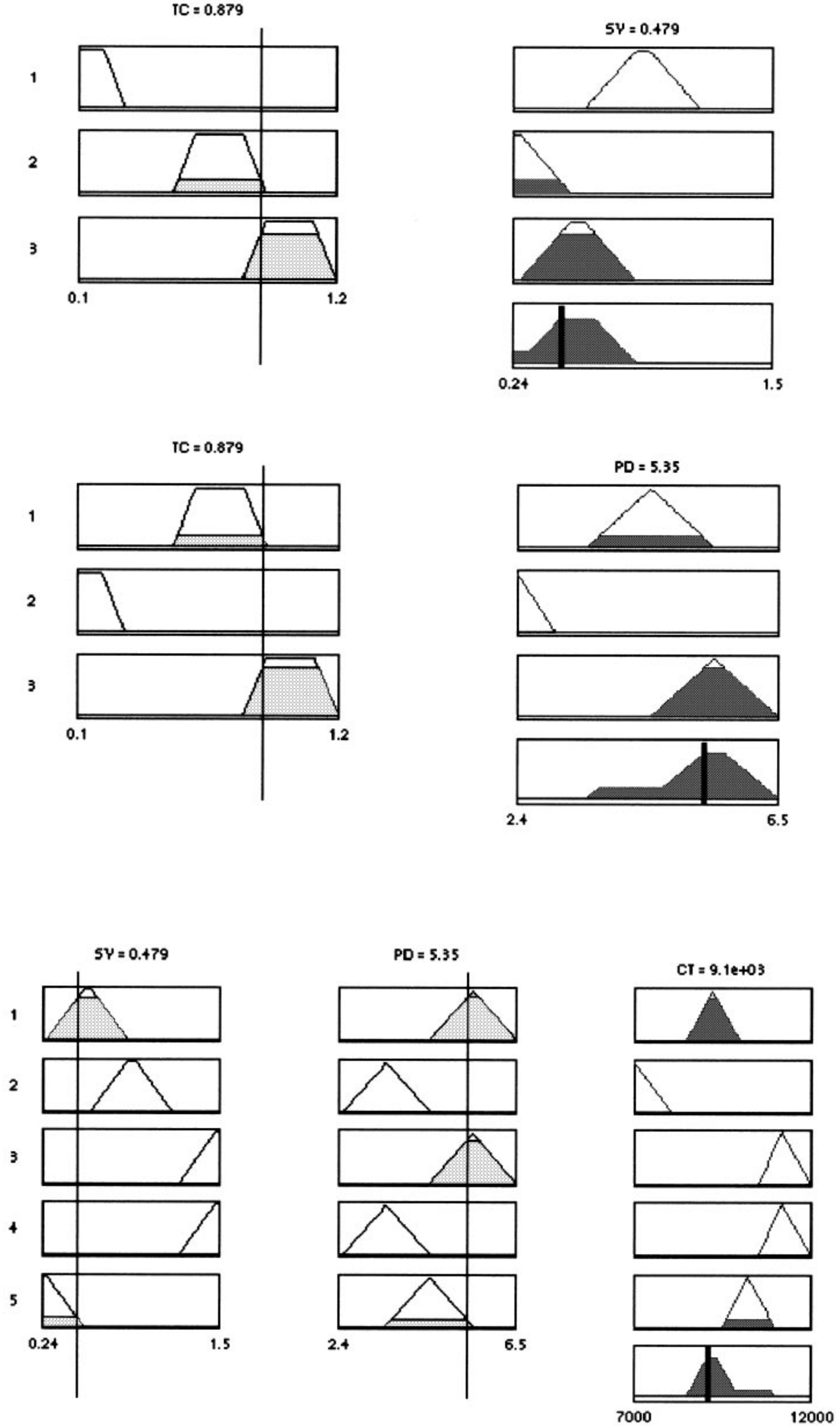

Fig. 9. Fuzzy reasoning of thin-film technology process.

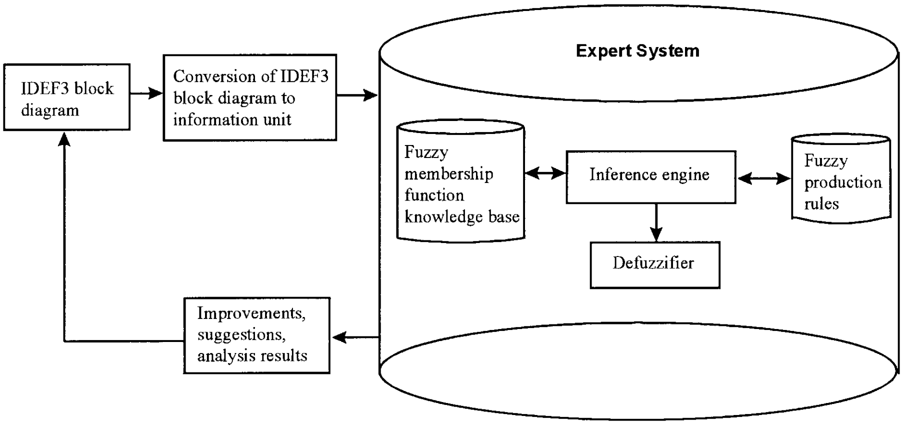

Fig. 10. Architecture of the expert system.

IDEF3 has been broadly accepted in numerous commercial and government establishments [25]. The most frequently recognised shortcoming of process modelling is the lack of analysis tools, because mathematical techniques are difficult to apply, owing to the qualitative nature of the models.

In this paper, a methodology for the analysis of process models was presented. The membership function of fuzzy sets was used to represent uncertain and incomplete information of process variables. The fuzzy-rule-based reasoning approach was integrated with an IDEF3 methodology for quantitative analysis of process models. The effectiveness of the approach was illustrated with an industrial example. Based on the procedure described in this paper, an expert system for analysis of process models was also outlined.

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