Analysis of Process Models

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***Abstract*—Process modeling tools, such as the integrated Definition (IDEF) methodology, allow for a systematic representation of processes in manufacturing, product development, and service applications. Most of the process modeling methodologies are based on informal notation, lack mathematical rigor, and are static and qualitative, thus difficult to be used for analysis. In this paper, a new analysis approach for process models based on signed directed graphs (SDG's) and fuzzy sets is presented. A membership function of fuzzy sets quantifies and transforms incomplete and ambiguous information of process variables into an SDG qualitative model. The effectiveness of the approach is illustrated with an industrial example. The architecture of an intelligent system for qualitative/quantitative analysis of process models is presented.**

***Index Terms*—Approximate reasoning, fuzzy sets, process models, quantitative analysis.**

I. INTRODUCTION

A PROCESS model includes a set of activities arranged in a specific order, with the clearly identified inputs and outputs. The output may be either a product or service [1]. Each activity in a process takes an input and transforms it into an output with some value to a customer. Ideally, every 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. In this section, several of the existing process modeling methodologies and tools are described. They vary in scope, appearance, and theoretical foundations.

A. CIM-OSA

Computer integrated manufacturing—open systems architecture (CIM-OSA) was developed by the ESPRIT Consortium AMICE [2]. The methodology facilitates system modeling through a process that includes system requirement definitions, system design specifications, and a system implementation description. Four system views (perspectives) are considered: functional, informational, resource, and organization [3].

B. OMM

The object-oriented modeling methodology (OMM) for manufacturing includes analysis and design phases [4]. The first task of the analysis phase is to decompose the system's functions into component functions using an approach similar to IDEF (discussed later in this paper). After a functional model has been constructed, function tables, data tables, and operation tables are generated. In the design phase, the object-oriented paradigm is used to translate the function tables, data tables, and operation tables into an integrated information model. Classes consisting of an identifier, attributes, and methods are defined for components of the system.

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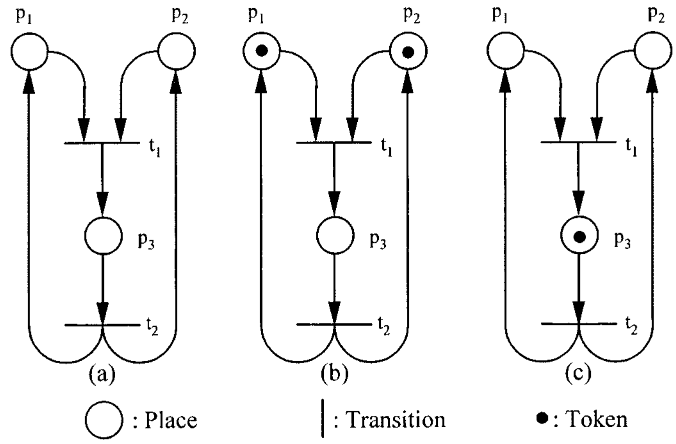

Fig. 1. Petri net of an activity that uses two resources: (a) Petri net model, (b) initial marking, and (c) marking after t_1 has been fired.

C. MOSYS

MOSYS is a software tool for modeling the functional structure, topology, and control rules of systems [5]. The functions of system are described with five building blocks: manufacture, transport, store, assemble, and test. These blocks are parametric and they can be customized to a specific application.

D. Petri Nets

A Petri net is a graphical modeling tool [6]. It consists of places (P), transitions (T), and arcs (see Fig. 1). Input arcs connect places with transitions, while output arcs start at a transition and end at a place. Places may contain tokens. Transitions, which model activities, may occur (the transition fires), thus changing the state of the system (the marking of the Petri net). A marking in a Petri net is a vector M that specifies the assignment of tokens to the places, i.e., $M : P/N$, $N \geq 0$. An initial state of a Petri net is called the initial marking, M_0. Transitions are only allowed to fire if they are enabled (all the preconditions for the activity are fulfilled). When the transition fires, it removes tokens from its input places and adds them to the output places. The number of tokens removed/added depends on the cardinality of each arc. Consider a process that consists of only one activity. To execute the activity, two resources have to be used. The net in Fig. 1(a) models this process, where

$P = \{p_1, p_2, p_3\}, T = \{t_1, t_2\}, M_0 = (1\ 1\ 0)$. Transition t_1 in Fig. 1(b) is enabled because each of its input places, p_1 and p_2, contains a token. When a transition is enabled, it can be fired. After firing the transition t_1, the output place of t_1, p_3, gets a token, the new marking M' is $(0\ 0\ 1)$ [Fig. 1(c)].

Petri nets are promising for representing systems that are concurrent, asynchronous, distributed, parallel, nondeterministic, and/or stochastic.

Several other process modeling techniques have been discussed in the literature. Johansson *et al*. [7] presented a simple technique for modeling sequential processes. Tsang [8] and Sheleg [9] discussed a technique based on business events for reengineering corporations, however, they did not support their ideas with a modeling example.

Based on some of the above methodologies, a number of process modeling tools have been developed, e.g., ARIS (Germany), FirstStep (Canada), PrimeObjects (Italy), TEMAS (Switzerland), and Scitor (USA) [see the link at http://www.icaen.uiowa.edu/~coneng/].

An important attribute of a modeling technique is extendibility, as a universal modeling 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 [10].

The integrated definition 3 (IDEF3) methodology offers several important characteristics for successful process representation: 1) process description in the form of activities, 2) structure of the underlying process, and 3) flow of objects and their relationship [11]. In spite of these advantages, IDEF3 methodology is static and qualitative, which is a drawback to analysis of processes [12]. 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.

Two other well established methodologies and tools deserve attention, the activity-based costing (ABC) and dynamic and discrete simulation.

ABC is a cost accounting concept that identifies activities performed, establishes the cost of each activity, and traces the cost of the activities to a product. Under ABC, costs can be assigned to each detailed activity and, subsequently, to each product or each component of a product [13], [14]. The major purpose of the ABC system is to provide more accurate information not only for costing of products and other cost objects, but also to facilitate decision making and process management. Many companies have successfully adopted ABC systems [13] and more than ten different software packages have been developed [15]. The deficiency of ABC analysis applied to process models is that it is appropriate for estimating the process cost but it does not well represent relations among activities.

A dynamic simulation model represents a set of linked differential equations describing a closed loop feedback system. Dynamic properties of the model can be analyzed by providing it with an appropriate set of parameters, initial conditions, and obtaining solutions with numerical integration procedures. The purpose of dynamic analysis of a process is to determine the behavior of the system under different initial inputs and to perform repeated experimentation with the model. The dynamic simulation model can be built using DYNAMO [16] or STELLA II [17] simulation modeling languages. Dynamic simulation allows one to perform qualitative analysis of a system and to represent the cause and effect relationships between activities. The major deficiency of the dynamic simulation is that it is a tool for analysis of continuous feedback systems, while process models are typically open loop. Model construction and validation becomes difficult as the size of systems modeled increases.

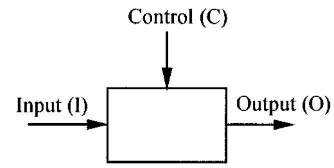

Fig. 2. IDEF3 activity box and interface arrows.

Discrete simulation models are used to analyze, explain, understand, or improve a process [18]. Several discrete simulation languages are available for building predictive process models, e.g., ARENA, SIMAN, SLAM, WITNESS. Discrete simulation models require a precise process definition and quantitative characterizations of activities. Another drawback of the discrete simulation approach is that it cannot represent the cause and effect relations among activities.

This paper applies and extends the analysis approach presented in Wang *et al*. [19] for analysis of IDEF3 process models. A framework is presented for integrating incomplete and quantitative process information into a qualitative process model. The quantitative process information is described with the fuzzy set theory. A framework of intelligent system for qualitative/quantitative analysis of IDEF3 process models is outlined.

E. IDEF Methodology

The IDEF methodology is a structured modeling technique, primarily intended for representing manufacturing systems. Initially, it was developed as a set of four methodologies, IDEF0, IDEF1, IDEF2, and IDEF3, for functional, data, dynamic analysis, and process modeling, respectively [10].

IDEF3 has been extensively used for modeling manufacturing processes. One of the major advantages of IDEF3 representation of processes is its simplicity and its descriptive power. IDEF methodology was developed in 1970s by the Integrated Computer Aided Manufacturing (ICAM) program. In this program, the industrial suppliers of the U.S. Air Force were to be given access to the state-of-the-art factory models that would help them to understand and ultimately redesign their own manufacturing processes. The IDEF3 model consists of three components: (1) hierarchically decomposed diagrams, (2) text for each of the diagrams, and (3) glossary of terms used in diagrams [11].

The two basic components of IDEF3 are a box and an arrow. Boxes represent activities, while the arrows represent interfaces. There are three different interfaces entering and exiting a box: input, output, and control (see Fig. 2). Inputs (I) enter the box from the left, are transformed by the activity, and exit the box to the right as an output (O). Control (C) enters the top of the box and influences or determines the activity performed. Replacing activity of the IDEF3 block in Fig. 2 with a function and entering a mechanism (M) interface from the bottom of box results in an IDEF0 block. A mechanism is a tool or resource needed to perform the function. The experience with industrial cases indicates that including a mechanism in IDEF3 is often useful, however, for the application presented in this paper there is no need for using mechanisms.

The essence of IDEF3 methodology is its ability to describe activities and their relationship 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 [10]. The relationship between activities in IDEF3 is modeled 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 modeled using an *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*. [20].

In the recent years, a number of papers have been published on analysis of IDEF models. Belhe and Kusiak [21] developed a procedure to generate alternative precedence networks from an IDEF3 network of design activities. They determined a lower bound on the completion time for the hierarchically structured network by extending an existing reduction procedure. Ang and Gay [22] 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 [23] integrated techniques for analysis of system reliability with an IDEF3 model. Kusiak and Zakarian [24], [25] developed a fault tree based methodology for reliability evaluation and risk assessment of parent activities of an IDEF3 model. The system reliability evaluation techniques were extended for analysis of IDEF3 models. The approaches presented in the above papers assume that the exact quantitative information of IDEF process variables, such as the reliability [23]–[25] and processing time of each activity [21] are available. However, in practice, this is not always the case. The activities in process model might be on a high level of abstraction and precise quantification of process variables may be complex. As an example consider the IDEF3 model of film deposition process shown in Fig. 3 with the activities, process variables, symbols, and units listed in Table I. Assume that the analyst wants to analyze reliability of the process of manufacture a circuit, or he/she attempts to evaluate the process completion time. Knowing the reliability and the processing time of each activity involved in the process, the approaches presented in [21] and [24] determine the reliability of the process and the lower bound on the duration of the process, respectively. However, evaluating the exact reliability of each activity, e.g., "Select material", is not a trivial problem. Moreover, the techniques developed in the literature do not consider the cause and effect relationship among process variables. For example, in analysis of the process in Fig. 3 it is important to know how the output of activity "Select material" (i.e., thermal conductivity) affects the quality of the sputtering operation (i.e., sputtering yield), or how the quality of sputtering operation affects the quality of pattern plating (i.e., plating density), and how the quality of pattern plating affects the quality of the final circuit (i.e., circuit thickness). In this paper, an approach based on Signed Directed Graphs (SDG's) is used to represent the cause and effect relations among activities of an IDEF3 model. Wang *et al*. [19] presented a fuzzy qualitative approach for interpreting dynamic process data. The analysis approach based on SDG's, fuzzy neural nets, and fuzzy set covering method was developed for fault diagnosis of chemical processes. This paper uses and extends the reasoning framework presented in [19] for qualitative/quantitative analysis of IDEF3 process models.

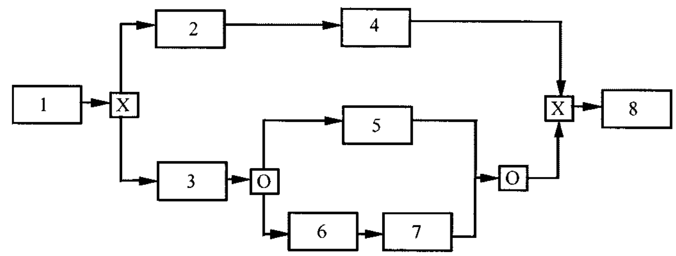

Fig. 3. IDEF3 model of the film deposition process.

II. Signed Directed Graphs

A Signed Directed Graph (SDG) is a digraph that have been used by many researchers for process analysis (see [19], [26], and [27]). One may define a SDG as $G \equiv (V, E, \Lambda, \Delta)$, where V is the vertex set, E is called signed directed edge set or link influence, Δ represent the change in the process variable, function, $\Lambda : E \rightarrow \{+, -\}$ represent the forward influence in the direction of an edge. A SDG is constructed to represent the cause-effect relations among process variables and to exhibit the process behavior. The vertex (node) of an SDG represents a process variable and the edge (link) represents the qualitative influence of a process variable on the related variable. For example, consider the graph in Fig. 4. The qualitative relationship between X_1 and X_2 can be described as follows. Nodes X_1 and X_2 represent process variables, e.g., thermal conductivity, layer density, time, reliability, etc. The sign on the edge represents the direction of influence and takes the value of "$+$," "0," or "$-$." The sign "$+$" implies, a positive (negative) deviation of X_1 leads to a positive (negative) deviation of X_2. When the sign on the edge is "$-$," an increase (decrease) in X_1 leads to decrease (increase) in X_2.

Once an IDEF3 process model is constructed and the relationship between process activities is defined, one can easily construct an SDG. When the qualitative model is available one is able to analyze the impact of process variables on the behavior of the process. For example, the qualitative state of X_2 in Fig. 4 is expressed as a positive

$$\mathrm{sign}(\Delta X_2) = \mathrm{sign}(\Delta X_1)\, \mathrm{sign}(X_1 \rightarrow X_2) \tag{1}$$

deviation of X_1 and positive branch between X_1 and X_2 results in a positive deviation of X_2.

TABLE I
IDEF3 MODEL ACTIVITY NAMES, PROCESS VARIABLES, SYMBOLS, AND UNITS

No.	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 fruitless 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

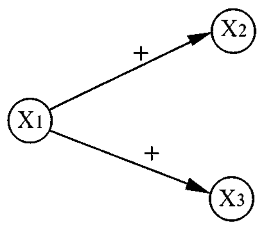

Fig. 4. Signed directed graph.

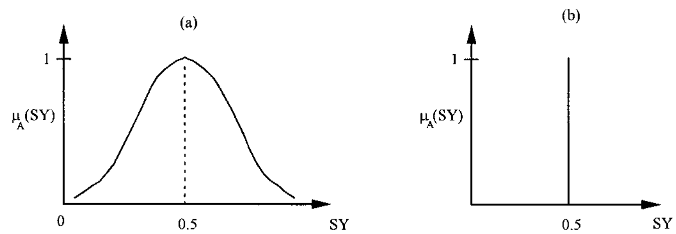

Fig. 5. Membership functions representing different propositions: (a) "the yield of sputtering operation is close to 0.5" and (b) "the yield of sputtering operation is 0.5."

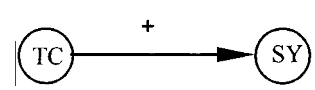

Fig. 6. SDG describing relationship between activities "select a material" and "perform sputtering."

An SDG represents qualitative information. To integrate the quantitative process information into a qualitative model of SDG's, the framework based on the membership functions of fuzzy set theory is discussed next.

III. Fuzzy Sets and Fuzzy Signed Directed Graphs

The theory of fuzzy sets [28] deals with a subset of the universe of discourse, where the transition between full membership and nonmembership is gradual rather than abrupt. For the 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 is 0.

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

A fuzzy SDG generalizes a crisp graph using fuzzy sets. A fuzzy graph is a pair $(\tilde{X}, \tilde{E})$, where $\tilde{X}$ is a finite fuzzy set of nodes and $\tilde{E}$ is a fuzzy relation on $X \times X$, such that $\mu_{\tilde{E}} \leq \min(\mu_{\tilde{X}}(x), (\mu_{\tilde{X}}(x'))$. Here $\mu_{\tilde{E}}$ is the membership function of the binary effect of two adjacent nodes x and x' over a branch, $\mu_{\tilde{X}}$ is the membership function of the node [29].

The membership function of fuzzy set provides a convenient way to describe a degree of belonging. Furthermore, the membership function can be described graphically. For example, Fig. 5(a) can be thought of as a representation of the proposition "the yield of sputtering operation is close to 0.5." The membership function can also describe a crisp concept. For example, the proposition "the yield of sputtering operation is 0.5" is described by the membership function in Fig. 5(b).

To illustrate the application of SDG and fuzzy sets (fuzzy SDG's) to qualitative and quantitative analysis of process models, consider the qualitative model representing relationship between activities "Select a material" and "Perform sputtering" in Fig. 3 described by the SDG in Fig. 6. Nodes TC and SY represent the process variables, thermal conductivity of a material selected and yield of sputtering operation, respectively. The sign on the branch from TC to SY implies that a positive deviation of TC leads to a positive deviation of SY. In other words, the higher the thermal conductivity of the material selected, the better yield of sputtering operation. The binary relationship between TC and SY can be described by the ratio $\Delta\mathrm{SY}/\Delta\mathrm{TC}$ taking values ranging from 0 to infinity. The membership function $\mu_{\mathrm{SY/TC}}$ takes the value 1 for all positive $\Delta\mathrm{SY}/\Delta\mathrm{TC}$ [see Fig. 7(a)]. Therefore, the qualitative relationship of activities can be described by the fuzzy set with the sign replaced by a membership function. Once the quantitative information is available, one can shape the membership function with a tighter constraint. For example, if the gain

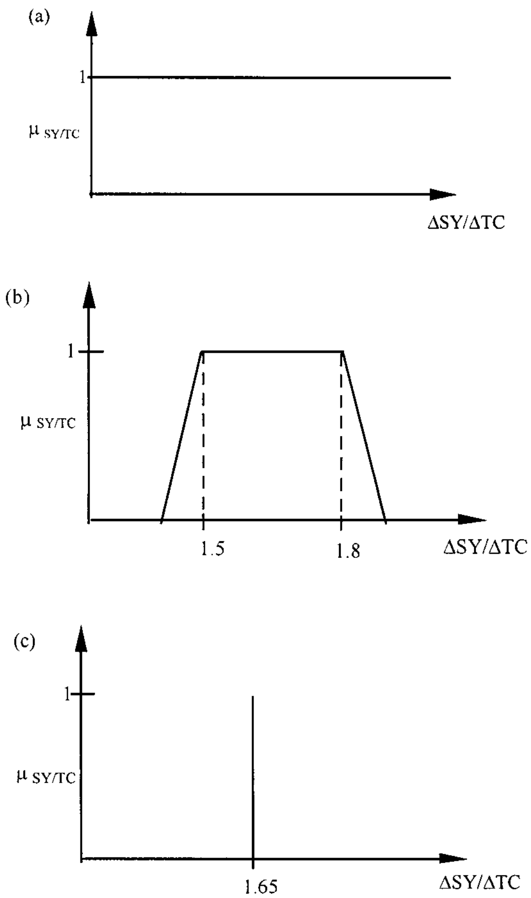

Fig. 7. Membership function for the ratio $\Delta\mathrm{SY}/\Delta\mathrm{TC}$.

between TC and SY ranges from 1.5 to 1.8, the membership function in Fig. 7(a) is modified to the one shown in Fig. 7(b). One may see that the membership function in Fig. 7(b) represents a quantitative information that by tightening the range of $\Delta\mathrm{SY}/\Delta\mathrm{TC}$ leads to a full membership. When one knows that the gain is 1.65, $\mu_{\mathrm{SY}/\mathrm{TC}}$ is equivalent to the function in Fig. 7(c), reflecting the quantitative relationship between the activities "select a material" and "perform sputtering."

The SDG and the membership functions presented above provide basis for a reasoning strategy of an IDEF3 process. For example, consider the SDG in Fig. 6 and the membership function $\mu_{\mathrm{SY}/\mathrm{TC}}$ in Fig. 7(b). With $\Delta\mathrm{TC}$ known, the change in the sputtering yield $\Delta\mathrm{SY}$ can be obtained from (2).

$$\Delta\mathrm{SY} = \mu_{\mathrm{SY}/\mathrm{TC}} \otimes \Delta\mathrm{TC} \tag{2}$$

where: $\mu_{\mathrm{SY}/\mathrm{TC}}$ is a fuzzy number defined by the membership function in Fig. 7(b),

$\otimes$ is the fuzzy multiplication operator.

The result of (2), i.e., the multiplication of $\mu_{\mathrm{SY}/\mathrm{TC}}$ (fuzzy number) and $\Delta\mathrm{TC}$ (crisp number), is a fuzzy number [30]. Therefore, expression (2) provides the range of change of process variable SY. Assuming the initial value of process variable SY is known, the range of current value of SY is obtained from (3)

$$\mathrm{SY} = \mathrm{SY}_{\mathrm{initial}} + \Delta\mathrm{SY}. \tag{3}$$

Furthermore, the approach presented here allows for backward reasoning with process models. For example, with $\Delta\mathrm{SY}$ known, the membership value $\mu_{\mathrm{SY}/\mathrm{TC}}$ can be determined from the membership function in Fig. 7(b). Then the value of $\Delta\mathrm{TC}$ can be calculated from (2) by solving it for $\Delta\mathrm{TC}$ and the value of actual process variable TC is obtained from (4)

$$\mathrm{TC} = \mathrm{TC}_{\mathrm{initial}} + \Delta\mathrm{TC}. \tag{4}$$

The concept of path sets can be used to identify the various scenarios in a process. A path set in an IDEF3 model is a set of all activities that define a path from source node to terminal node in the model. Therefore, from a path set the impact of the source node on the terminal node can be determined. Several algorithms are available for determining path sets of IDEF3 models (see [24], [21], [31], [32]). Once the path sets of an IDEF3 model have been generated, the qualitative SDG model is constructed for each scenario. The membership functions describe the quantitative relationship between the activities included in a path set. The forward and backward reasoning strategies are used to perform quantitative analysis of the model. The overall system architecture for qualitative/quantitative analysis of process models is shown in Fig. 8.

IV. Industrial Application

The IDEF3 model of the film deposition process presented in Fig. 3 is used to illustrate the approach discussed in the paper [33]. The example presents a small component of manufacturing process taken from an industrial company. At the first level of abstraction, eight activities are included. The first activity in the model is to select 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). The exclusive OR junction in Fig. 3 indicates this relationship. If a thin film technology is selected, the sputtering operation is followed by the perform pattern plating activity. If MOD film technology is selected, then the screen printing activity is performed and the final layer is obtained either by electroplating or by adding fruitless gold and performing subtractive etching. These relationships are reflected by the OR junction and the precedence link. The second exclusive OR junction implies that the process converges at that point back into a single stream.

The initial values of process variables obtained from process engineers and shown in Table II. Furthermore, the trapezoidal membership function is used (see Fig. 9) to describe the relationship between process variables. However, it is important to emphasize that the membership function may take various shapes, not necessarily trapezoidal.

The membership values of the function in Fig. 9 are calculated from (5)

$$\mu(x) = \begin{cases} 0, & -\infty < x \le -a_2 \\ \dfrac{a_2 + x}{a_2 - a_1}, & -a_2 \le x \le -a_1 \\ 1, & -a_1 \le x \le -a_1 \\ \dfrac{a_2 - x}{a_2 - a_1}, & a_1 \le x \le a_2 \\ 0, & a_1 \le x < \infty. \end{cases} \tag{5}$$

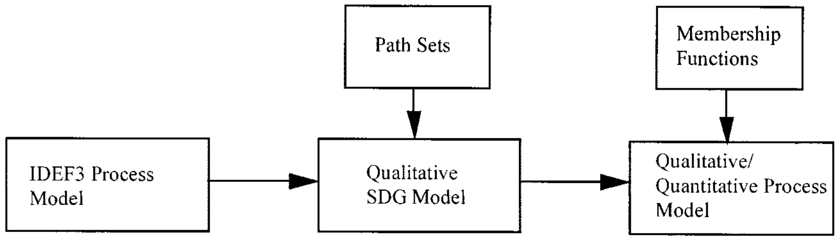

Fig. 8. Structure of the proposed approach for analysis of process models.

TABLE II
INITIAL VALUES OF PROCESS VARIABLES OF THE IDEF3 PROCESS IN Fig. 3

	Process variable							
Activity	1	2	3	4	5	6	7	8
Symbol/ Unit	TC cal s^{-1} cm^{-1}	SY atoms/ion	SR mil	PD g cm^{-3}	ED g cm^{-3}	LD g cm^{-3}	EAT Å	CT Å
Initial value	0.077	1.3	1.1	2.55	1.87	5.55	125	7,500

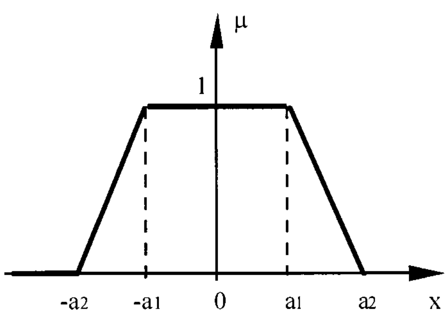

Fig. 9. Trapezoidal membership function.

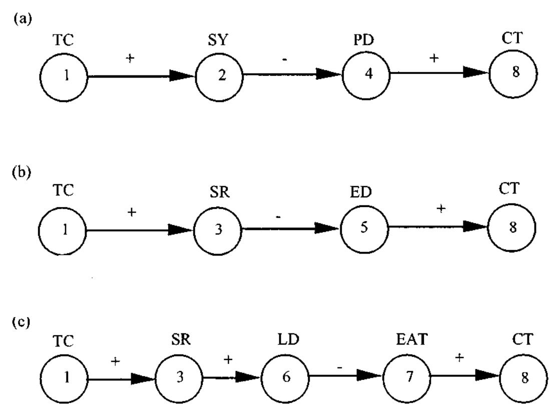

Fig. 10. SDG's of the IDEF3 model for three paths: (a) 1-2-4-8, (b) 1-3-5-8, and (c) 1-3-6-7-8.

First, the path sets 1-2-4-8, 1-3-5-8, and 1-3-6-7-8 of the IDEF3 model in Fig. 3 are determined. For small size models, similar to the one presented in Fig. 3, these sets could be possibly obtained by inspection of the model. However, when the number of activities and logical connectors in the model is large, formal approaches must be used. Once the path sets of the IDEF3 process are determined, an SDG for each path set is built (see Fig. 10).

The next step is to integrate the quantitative information into a qualitative model. The quantitative information may be obtained from the process simulation, knowledge base, or the actual process. In this case, the quantitative information is obtained from the manufacturing process knowledge base. For example, assume that the ratios of $\Delta\mathrm{SY}/\Delta\mathrm{TC}$, $\Delta\mathrm{PD}/\Delta\mathrm{SY}$, $\Delta\mathrm{CT}/\Delta\mathrm{PD}$ are around 38.35, -1.65, and 1015, respectively. The membership functions describing relations between process variables of the thin film technology are constructed accordingly [see Fig. 11(a)]. Similarly, the membership functions describing the relationships among process variables of the metallo-organic film technology are obtained [see Fig. 11(b) and (c)].

To illustrate the quantitative analysis of IDEF3 models, consider the results of forward reasoning computations presented in Table III. The example in Fig. 12 illustrates variables of thin film technology process calculated in a forward reasoning mode (path 1-2-4-8) in Table III. Table III shows that the change $\Delta\mathrm{TC} = -0.017$ in the thermal conductivity results in the circuit thickness produced by the thin film technology to vary from 862 to 1318 A. The same $\Delta\mathrm{TC} = -0.017$ causes the circuit thickness produced by the MOD film technology to vary between 666 and 1386 A (path 1-3-5-8) and between 1982 and 3309 A (for path 1-3-6-7-8). The changes of the remaining process variables $\Delta\mathrm{SY}$, $\Delta\mathrm{PD}$, $\Delta\mathrm{SR}$, $\Delta\mathrm{ED}$, $\Delta\mathrm{LD}$, and $\Delta\mathrm{EAT}$ are calculated from (2). Furthermore, the current values of process variables are obtained from (3).

Table IV presents results of backward reasoning for the industrial example. The analysis show, that in order to achieve the thickness of a circuit between 8500 and 8700 Å using the thin film technology (path 1-2-4-8), a change in the thermal conductivity between $-(0.01–0.024)$ is required. Moreover, the changes in other process variables, i.e., $\Delta\mathrm{SY}$ and $\Delta\mathrm{PD}$ are between $-(0.54–0.82)$ and 0.97–1.2, respectively. To obtain similar thickness for the final circuit built with

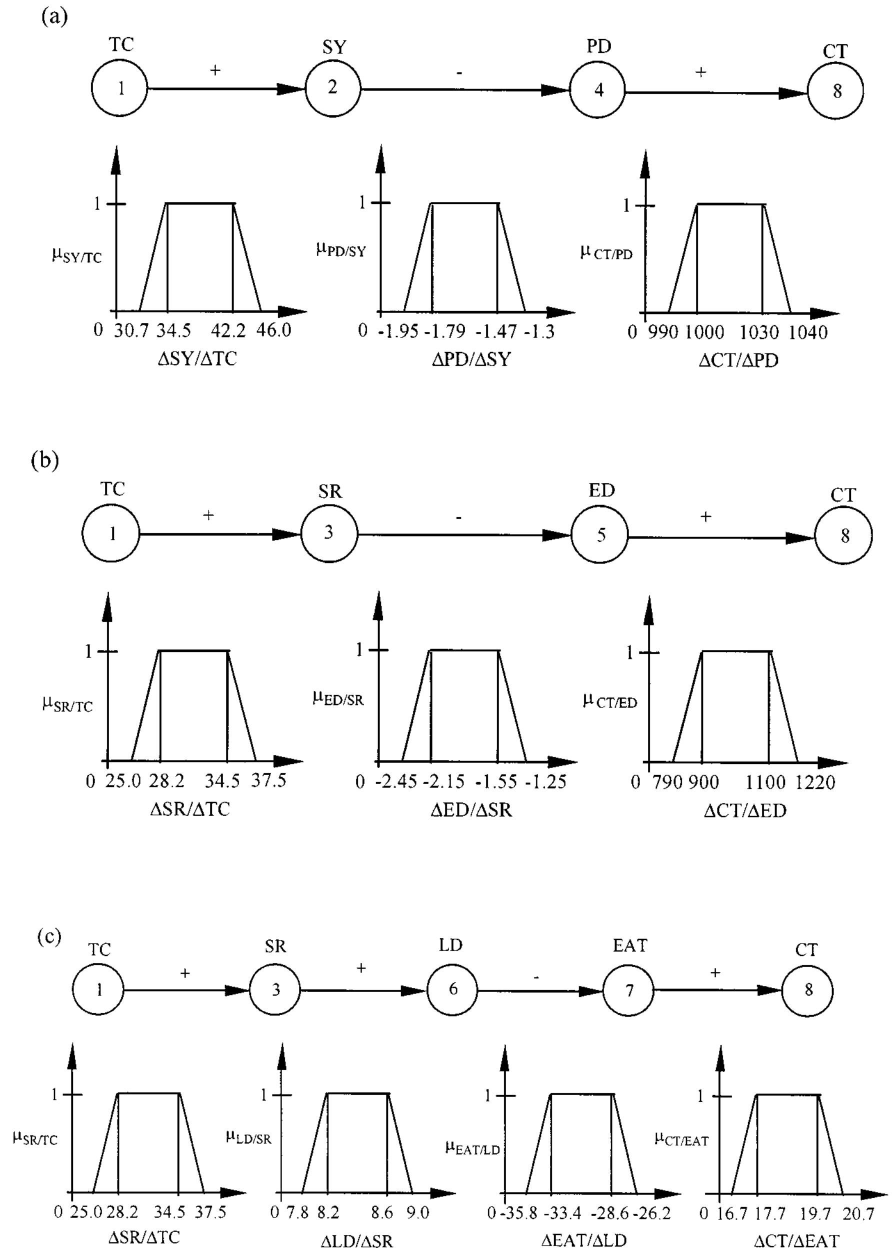

Fig. 11. Quantitative/qualitative models representing: (a) thin film technology (path 1-2-4-8), (b) MOD film technology (path 1-3-5-8), and (c) MOD film technology (path 1-3-6-7-8).

MOD technology, the changes in process variables, $\Delta\mathrm{TC}$, $\Delta\mathrm{SR}$, and $\Delta\mathrm{ED}$ (path 1-3-5-8) are between $-(0.012–0.03)$, $-(0.418–0.858)$, and 0.9–1.33, respectively, and the changes in process variables $\Delta\mathrm{TC}$, $\Delta\mathrm{SR}$, $\Delta\mathrm{LD}$, and $\Delta\mathrm{EAT}$ (path 1-3-6-7-8) are between $-(0.005–0.05)$, $-(0.18–0.29)$, $-(1.53–2.38)$, and 51–68. The ranges for the values of process variables in Table IV are obtained from (4).

It is important to emphasize that the membership functions of narrow shape tighten the range of values of process variables. The width of a membership function depends not only on the quantitative process information available, but also on the uncertainty of the process. Therefore, a narrow membership function may miss the true ratio of a process variable. Furthermore, in backward reasoning a smaller range for current value of CT can be obtained by selecting a smaller range of $\Delta\mathrm{CT}$.

The forward and backward reasoning strategy presented in this paper may be used for decision making by process engineers. The fun-out logical connectors in the IDEF3 model represent the decision points. The model in Fig. 3 contains two fun-out junctions, the Exclusive OR and OR, corresponding to the decision points following activities 1 and 3. Assume that a circuit thickness of at least 9400 A is required in the film deposition process. Once the material has been selected and the change in the thermal conductivity, $\Delta\mathrm{TC} = -0.017$ is observed, the process analyst should decide between two diverging paths following the first decision point, the exclusive OR junction (see Fig. 3). Using the forward reasoning strategy s/he may identify the path 1-3-6-7-8 in the model that yields the desired film thickness of 9400 Å. Similarly, once the screen printing (activity 3) is performed, the analyst should decide between the two diverging

TABLE III
FORWARD REASONING COMPUTATIONAL RESULTS FOR THE INDUSTRIAL EXAMPLE

	Process variable							
Activity	1	2	3	4	5	6	7	8
Symbol/ Units	TC cal s^{-1} cm^{-1}	SY atoms/ion	SR mil	PD g cm^{-3}	ED g cm^{-3}	LD g cm^{-3}	EAT Å	CT Å
Thin film technology Path (1-2-4-8)	0.06 Δ = - 0.017	0.583 ~ 0.714 Δ = - (0.586 ~ 0.717)		3.412 ~ 3.83 Δ = 0.862 ~ 1.28				8,362 ~ 8,818 Δ = 862 ~ 1,318
MOD film technology Path (1-3-5-8)	0.06 Δ = - 0.017		0.514 ~ 0.621 Δ = - (0.479 ~ 0.586)		2.61 ~ 3.13 Δ = 0.74 ~ 1.26			8,166 ~ 8,886 Δ = 666 ~ 1,386
MOD film technology Path (1-3-6-7-8)	0.06 Δ = - 0.017		0.514 ~ 0.621 Δ = - (0.479 ~ 0.586)			0.51 ~ 1.62 Δ = - (3.93 ~ 5.04)	237 ~ 293 Δ = 112 ~ 168	9,482 ~ 10,809 Δ = 1,982 ~ 3,309

ΔTC = − 0.017, then from (1):

sign(ΔSY) = sign(ΔTC) sign(TC $\rightarrow$ SY) = "–"

From (2) and Figure 11(a):

ΔSY = [0.586 ~ 0.717]

From (3):

SY = $SY_{initial}$ + ΔSY = 1.3 - [0.586 ~ 0.717] = [0.583 ~ 0.714]

Similarly, the values of PD and CT calculated as follows:

sign(ΔPD) = sign(ΔSY) sign(SY $\rightarrow$ PD) = "+"
ΔPD = [0.862 ~1.28]
PD = $PD_{initial}$ + ΔPD = 2.55 + [0.862 ~ 1.28] = [3.412 ~ 3.83]

sign(ΔCT) = sign(ΔPD) sign(PD $\rightarrow$ CT) = "+"
ΔCT = [862 ~ 1318]
CT = $CT_{initial}$ + ΔCT = 7500 + [862 ~ 1318] = [8362 ~ 8818]

Fig. 12. Forward reasoning computations for thin film technology process variables (path 1-2-4-8).

paths following the second decision point, i.e., the OR junction. Once again the forward reasoning approach presented in this section allows one to identify activities that yield the required thickness of a circuit (here activity 6 and 7). When the required circuit thickness is between 8400 and 8600 Å, then at the first decision point a choice between the two diverging paths 1-2-4-8 and 1-3-5-8 is to be made. Here, a path may be selected based on the desired values of other process variables.

A. Model Extension

The analysis approach presented so far considers the relationship between two activities in the process. However, it is possible that an activity is influenced by more than one activity. For example, for the film deposition process (path 1-3-6-7-8) in Fig. 3 assume that the activities "Obtain final layer by adding fruitless gold" (activity 6) and "Perform subtractive etching" (activity 7) are performed in parallel, i.e., they are connected with an AND logical link (Fig. 13), and both influence the final thickness of a circuit. The SDG describing the qualitative relationship among the process variables LD, EAT, and CT is shown in Fig. 14. The membership functions describing the relationship among process variables LD, CT, EAT, and CT are illustrated in Fig. 15(a) and (b).

The problem here differs from the one discussed in Section III, since $\Delta\mathrm{CT}$ is the result of the combined effect of $\Delta\mathrm{LD}$ and $\Delta\mathrm{EAT}$. The digraph in Fig. 14 is equivalent to the algebraic (6) [34]

$$\Delta\mathrm{CT} = \Delta\mathrm{LD}\,\mu_{\mathrm{CT/LD}} \oplus \Delta\mathrm{EAT}\,\mu_{\mathrm{CT/EAT}} \tag{6}$$

where $\mu_{\mathrm{CT/LD}}$ is the membership function (fuzzy number) shown in Fig. 15(a), $\mu_{\mathrm{CT/EAT}}$ is the membership function (fuzzy number) shown in Fig. 15(b), and $\oplus$ is the fuzzy addition operator.

Note, if the sign on the edge $7 \rightarrow 8$ in Fig. 14 was negative, then the fuzzy addition in (6) should be replaced by the fuzzy subtraction operation.

The (6) corresponds to a trapezoid membership function with corners being the summation of the corners of each individual membership function in Fig. 15(a) and (b) [35]. Dividing both sides of (6) by $\Delta\mathrm{LD}$ results in (7)

$$\frac{\Delta\mathrm{CT}}{\Delta\mathrm{LD}} = \mu_{\mathrm{CT/LD}} \oplus \frac{\Delta\mathrm{EAT}}{\Delta\mathrm{LD}}\mu_{\mathrm{CT/EAT}} = \mu^{*}_{\mathrm{CT/LD}} \tag{7}$$

where $\mu^{*}_{\mathrm{CT/LD}}$ is the modified membership function describing the combined effect of $\Delta\mathrm{EAT}$ and $\Delta\mathrm{LD}$ on $\Delta\mathrm{CT}$.

Equation (7) shows that $\mu^{*}_{\mathrm{CT/LD}}$ is a function of $\mu_{\mathrm{CT/LD}}$, $\mu_{\mathrm{CT/EAT}}$ as well as of $\Delta\mathrm{EAT}$ and $\Delta\mathrm{LD}$. Similarly, $\mu^{*}_{\mathrm{CT/EAT}}$ is expressed by (8)

$$\frac{\Delta\mathrm{CT}}{\Delta\mathrm{EAT}} = \frac{\Delta\mathrm{LD}}{\Delta\mathrm{EAT}}\mu_{\mathrm{CT/LD}} \oplus \mu_{\mathrm{CT/EAT}} = \mu^{*}_{\mathrm{CT/EAT}}. \tag{8}$$

For example, when $\Delta\mathrm{EAT} = 40$, $\Delta\mathrm{LD} = 5$, and $\Delta\mathrm{CT} = 1800$, the modified membership functions $\mu^{*}_{\mathrm{CT/LD}}$

TABLE IV
BACKWARD REASONING COMPUTATIONAL RESULTS FOR THE INDUSTRIAL EXAMPLE

	Process variable							
Activity	1	2	3	4	5	6	7	8
Symbol/ Units	TC cal s^{-1} cm^{-1}	SY atoms/ion	SR mil	PD g cm^{-3}	ED g cm^{-3}	LD g cm^{-3}	EAT Å	CT Å
Thin film technology Path (1-2-4-8)	0.053 ~ 0.067 Δ = - (0.01 ~ 0.024)	0.48 ~ 0.76 Δ = - (0.54 ~ 0.82)		3.52 ~ 3.75 Δ = 0.97 ~ 1.2				8,500 ~ 8,700 Δ = 1,000 ~ 1,200
MOD film technology Path (1-3-5-8)	0.047 ~ 0.065 Δ = - (0.012 ~ 0.03)		0.242 ~ 0.682 Δ = - (0.418 ~ 0.858)		2.77 ~ 3.2 Δ = 0.9 ~ 1.33			8,500 ~ 8,700 Δ = 1,000 ~ 1,200
MOD film technology Path (1-3-6-7-8)	0.027 ~ 0.072 Δ = - (0.005 ~ 0.05)		0.81 ~ 0.92 Δ = - (0.18 ~ 0.29)			7.08 ~ 7.93 Δ = - (1.53 ~ 2.38)	176 ~ 193 Δ = 51 ~ 68	8,500 ~ 8,700 Δ = 1,000 ~ 1,200

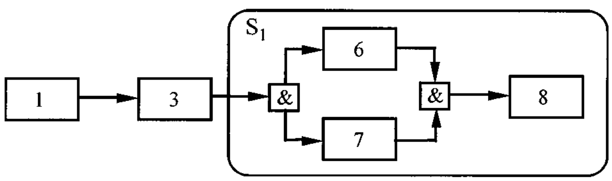

Fig. 13. Modified path 1-3-6-7-8 of the IDEF3 model.

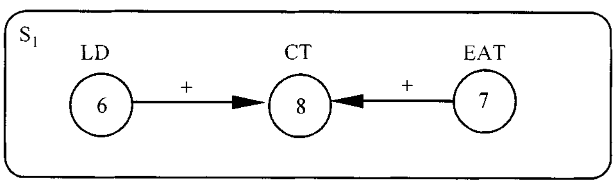

Fig. 14. SDG describing relationship between activities “Obtain final layer by adding fruitless gold,” “perform subtractive etching,” and “form a circuit.”

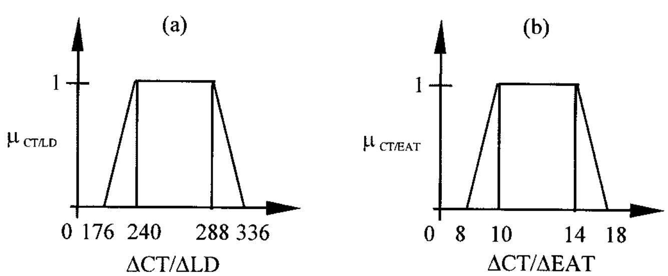

Fig. 15. Membership function for two ratios: (a) $\Delta\mathrm{CT}/\Delta\mathrm{LD}$ and (b) $\Delta\mathrm{CT}/\Delta\mathrm{EAT}$.

and $\mu^*_{\mathrm{CT/EAT}}$ [see Fig. 16(a) and (b)] are obtained from (7) and (8).

The consistency of the digraph in Fig. 14 can be checked using the following expresion [34]

$$\mu_{\mathrm{CT/LD\&EAT}} = \min\left[\mu_{\mathrm{CT/LD}}\left(\frac{\Delta\mathrm{CT}}{\Delta\mathrm{LD}}\right), \mu_{\mathrm{CT/EAT}}\left(\frac{\Delta\mathrm{CT}}{\Delta\mathrm{EAT}}\right)\right]. \quad (9)$$

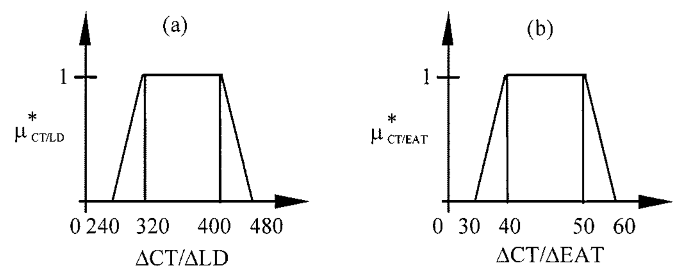

Fig. 16. Membership functions: (a) $\mu^*_{\mathrm{CT/LD}}$ and (b) $\mu^*_{\mathrm{CT/EAT}}$.

From the membership functions $\mu^*_{\mathrm{CT/LD}}$ and $\mu^*_{\mathrm{CT/EAT}}$ [Fig. 16(a) and (b)], the truth value of (9) is

$$\mu_{\mathrm{CT/LD\&EAT}} = \min\left[\mu_{\mathrm{CT/LD}}\left(\frac{1800}{5}\right), \mu_{\mathrm{CT/EAT}}\left(\frac{1800}{40}\right)\right] = 1.$$

The approach described above can be used for analysis of process models with parallel activities. For example, consider the modified path 1-3-6-7-8 of the IDEF3 model in Fig. 13. Once the membership function in Fig. 16(a) is obtained, one may construct the quantitative/qualitative model (see Fig. 17) for the IDEF3 process in Fig. 13. The membership function $\mu^*_{\mathrm{CT/LD}}$ in Fig. 17 is placed between nodes 67 and 8 to represent the combined effect of $\Delta\mathrm{EAT}$ and $\Delta\mathrm{LD}$ on $\Delta\mathrm{CT}$. Two membership functions corresponding to the ratios $\Delta\mathrm{EAT}/\Delta\mathrm{SR}$ and $\Delta\mathrm{LD}/\Delta\mathrm{SR}$ are placed between nodes 3 and 67. Although, only $\Delta\mathrm{LD}$ is required to obtain the final thickness of a circuit, the value of $\Delta\mathrm{EAT}$ is important for the overall process analysis.

V. INTELLIGENT SYSTEM FOR QUANTITATIVE ANALYSIS OF PROCESS MODELS

The procedure described in this paper provides the basis of an intelligent system for qualitative/quantitative analysis of process models. The proposed intelligent system includes a model base, data dictionary, qualitative analysis knowledge base, quantitative analysis knowledge base, and a process analysis module. The overall system architecture is presented in Fig. 18. The

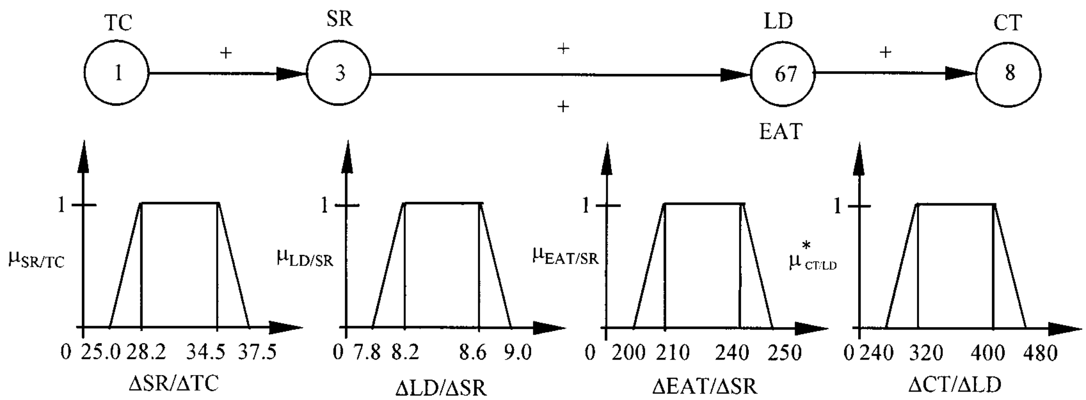

Fig. 17. Quantitative/qualitative model of the modified IDEF3 process in Fig. 13.

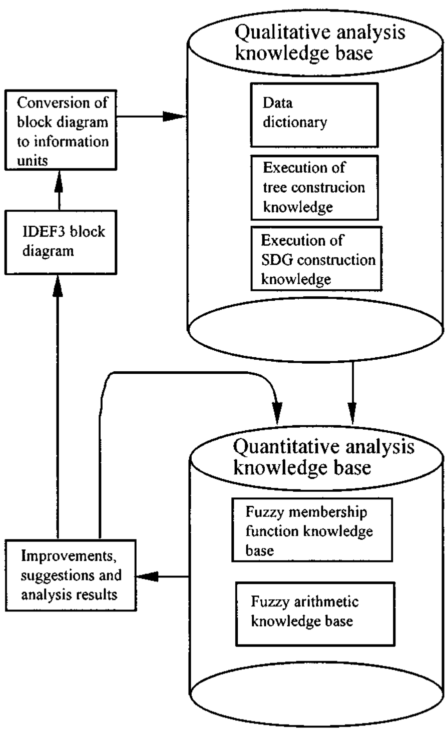

Fig. 18. Architecture of the qualitative/quantitative analysis module.

knowledge base accepts graphical input in the form of IDEF3 block diagram and uses the data dictionary (containing the information about all activities, process variables, and logical connectors of the model). Various scenarios of a process are identified. For each scenario an SDG is constructed. The knowledge base integrates the quantitative information into a qualitative model. The analysis is performed with the fuzzy arithmetic module model.

VI. Conclusion

The IDEF3 methodology lends itself to the representation of manufacturing, product development, and business processes. It has been broadly accepted for commercial and government applications [36]. The most frequently recognized shortcoming of process modeling may be the lack of analysis tools. Due to the qualitative nature of models, mathematical techniques are difficult to apply. In this paper, a method for qualitative/quantitative analysis of process models was presented. A qualitative model highlighting the cause/effect relationships of process activities, was constructed based on the fuzzy SDG approach. Membership functions were used to integrate the incomplete and ambiguous information of process variables into a qualitative model. Extension of the analysis to process models with parallel activities was presented.

Furthermore, several process modeling techniques were discussed and compared with the IDEF methodology. The important advantage of the methodology and the quantitative/qualitative analysis module developed in this paper is in their extendibility. The methodology developed in this paper can be used for analysis of process models based on the first order logic and graphical syntax. Furthermore, the approach developed in this paper can be used to analyze processes represented with any tool, provided that an modification of the data dictionary is made.

Future research issues include: 1) transformation of quantitative information into a knowledge-based system and 2) development of reasoning strategies and algorithms for model analysis [37].

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