Manufacturing-Oriented Discrete Process Modeling Approach Using the Predicate Logic

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Abstract—Part machining is a discrete manufacturing process. In order to evaluate the manufacturing process, an intelligent modeling method based on the first-order predicate logic is proposed. First, the basic predicate formula is defined according to the machining method, and the predicate and variables are illustrated in detail. Thus, the process representation is completed. Second, to construct the process model, the modeling element is put forward, which includes three nodes. Components of modeling element are, respectively, discussed, as well as the mapping relationship between modeling element and predicate. After the definition of modeling predicate formula, five basic inference rules are established. Consequently, the manufacturing process model is constructed. Third, on the basis of the process model, the process simulation is carried out to evaluate the manufacturing performances, such as the production efficiency, the utilization rate of machining equipment, the production bottleneck, etc. Finally, a case study is conducted to explain this modeling method.

Index Terms—Discrete process, intelligent modeling, predicate logic, performance simulation.

1 Introduction

In industry, manufacturing of a part can be normally decomposed into a sequence of machining steps which is always designed by the process department. In the past, reports showed that this sequence spans 60-70 percent of the whole production cycle time. To optimize the process plan, the manufacturing process need be modeled and analyzed. And the manufacturing performances in terms of production efficiency, bottleneck, cost, and time are evaluated for improvement.

At present, the modeling method is one of the main research directions of manufacturing process. During past years, many modeling methods have been proposed. Among these existing modeling methods, Petri net, IDEFx, and Object-oriented methods have been most widely adopted in engineering. The simulation of timed Petri-net-based model was used to construct the process model and analyze the transient and the steady-state behaviors of manufacturing process, and an efficient algorithm was proposed to execute the timed Petri net model [1]; to realize the integration of computer-aided process planning (CAPP) and the production planning and scheduling, a flexible process model based on Petri net was brought forward by Jinliang and Zhiyong [2]. The cost optimization for the process planning based on the Petri net model was also investigated [3]; the modeling of the Flexible Manufacturing System (FMS) using Petri net was discussed to determine the manufacturing behaviors. Moreover, the interface of the transformation rules from an IDEF0 specification into a Petri net was developed to generate automatically the control logic [4]; van Rensburg [5] and Kim et al., respectively, discussed the implementation of IDEF method in the modeling simulation [6]; an object-oriented modeling method was proposed to realize the agile manufacturing [7]; and the object-oriented modeling and simulation of flexible manufacturing system was discussed further in detail [8]. Besides, a fuzzy modeling was put forward to deal with the cost and time estimation in flat-plate processing [9]. However, the above modeling methods need manual work, and their models cannot be reused when modeling preconditions change; hence, too many efforts are required to construct the process model. Therefore, these methods lack of the ability of flexible modeling and the modeling efficiency is low.

By far, there are few reports about manufacturing process modeling using the first-order predicate logic. So, an approach of intelligent modeling, based on the first-order predicate logic, is presented to realize the process modeling in this paper. First, the first-order predicate logic representation of process procedure is discussed in detail. Then, the process modeling is automatically completed by logical inference of process procedure. Third, the process simulation is conducted to evaluate the manufacturing performances on the basis of the process model. Finally, an application case is taken as an example to illustrate this method.

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2 Process Representation

Obviously, the key problems of discrete process modeling include the representation of discrete process, the construction of modeling element, the modeling process, and the process simulation. In this paper, the first-order predicate logic is used in the discrete process modeling.

As far as this modeling method is concerned, the process procedure is expressed as a series of predicate logic formulas in the form of the first-order predicate logic. Generally, manufacturing process consists of machining equipment, process method, and machining requirements. Machining equipment represents the machining subject, the process method indicates the machining behaviors, and the machining requirement implies the machining objective.

Predicate P is defined according to the process method. Predicate variables include the machining object MO, the machining equipment MT, and the machining requirement MR. The predicate formula is expressed as

$$Process\_Name\ (MT, MO, MR), \tag{1}$$

where the compound word *Process_Name* denotes the predicate, such as *Pro-Lathing*, *Pro-drilling*, etc. The semantic meaning of predicate logic formula (1) is explained as "Use the MT to *Process_Name* the MO according to the MR." Thus, the process item can be represented as the first-order predicate logic formula. It is known that a process item may be expressed as lots of different predicate logic formulas. These different predicate logic formulas are connected through the disjunction connective "$\vee$."

A modeling element is put forward to realize the intelligent modeling of process procedure, as shown in Fig. 1. The modeling element consists of four nodes and three links. Nodes are, respectively, represented as the symbol FD, ID, and SD. The functional node FD can be, respectively, connected with the information node ID and the resource node SD through the information link and the resource link. The functional node FD is the output end and the resource node SD is the input end. Among three links, the power value w in the resource link expresses the amount of raw material. The functional node FD represents the machining equipments, such as lathe and grinding machine. The resource node SD represents the machining resources, such as the raw material and final products. In the process simulation, the resource node SD is quantified as the amount of production material. The information node ID expresses the manufacturing information, such as the manufacturing requirements, manufacturing dimension, and tolerance. Therefore, the process procedure can be represented as the process model.

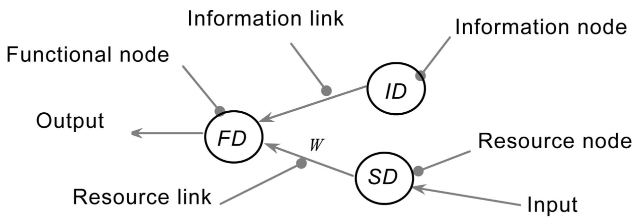

Fig. 1. Construction of modeling element.

3 Modeling Process

Modeling process mainly includes the inference rule and the inference process. The inference rule provides the bridge between the predicate formula of process procedure and the process model. The inference process provides the principles to realize the connection of modeling element. As a result, the process model can be constructed. First, the predicate formula of logical inference is defined as

$$Node\text{-}Connection(a, b). \tag{2}$$

This predicate formula expresses that node a is connected with node b, and the source flower direction is from the node a to the node b. Based on the production practice, five basic inference rules which can reflect the process procedure as enough as possible are lay down under condition of the simply production pattern. For other production patterns, additional inference rule can be worked out on the basis of five basic inference rules. Five basic inference rules are explained as follows:

1. $Process\text{-}Name(FD_1, SD_1, ID_1) \wedge Process\text{-}Name(FD_2, SD_2, ID_1) \rightarrow Node\text{-}Connection(SD_1, FD_2)$.
   This rule shows that different machining equipments carry out the same machining task.
2. $Process\text{-}Name(FD_1, SD_1, ID_1) \wedge Process\text{-}Name(FD_1, SD_1, ID_2) \rightarrow Node\text{-}Connection(ID_2, FD_1)$.
   This rule indicates that the same machining equipment is arranged to many different machining tasks.
3. $Process\text{-}Name(FD_1, SD_1, ID_1) \wedge Process\text{-}Name(FD_2, SD_2, ID_2) \rightarrow Node\text{-}Connection(FD_1, SD_2)$.
   This rule connects related nodes for adjacent manufacturing tasks.
4. $Process\text{-}Name(FD, SD, ID) \rightarrow Node\text{-}Connection(ID, FD) \wedge Node\text{-}Connection(SD, FD)$.
   This rule is used to build the modeling element according to the predicate logic of process item.
5. The different predicate formulas of the same procedure item are connected through the disjunction "$\vee$" and the different predicate formulas of adjacent process items are connected through the conjunction "$\wedge$."

Generally, process items in the process procedure are sequentially arranged according to the machining sequence, and there are close associations between adjacent process items. Therefore, logical inference should enable to solve two problems. The one is the logical inference of single predicate formula, and the other is the logical inference of adjacent predicate formulas. The former is used to determine the inference result of single process item, and the latter is to determine the inference result of adjacent process items. The logical inference of adjacent predicate formulas is sequentially performed according to the process procedure. Then, the inference result of single predicate formula is connected with the inference result of adjacent predicate formulas through the conjunction "$\wedge$." Consequently, a series of submodels are constructed through the above inference process. Finally, the process model can be built through the integration of all submodels.

4 Process Simulation

After the construction of process model, the manufacturing performances can be evaluated by process simulation. The main objectives of process simulation are to define simulation variables, to determine the simulation algorithm and analyze the manufacturing behavior. From components of process procedure, it can be seen that manufacturing process contains lots of information, and information is classified into three type nodes—*FD, SD, ID*. Among these nodes, resource node SD expresses the utilization state of raw material. Manufacturing process comes to end when raw material is used up. The production state at any time can be expressed by the amount of raw material. Therefore, the resource node SD is regarded as a simulation variable-resource vector RD. The relationship between the functional node FD and the resource node SD is described by the resource link. Through this link, modeling elements are connected each other to construct the process model, and process simulation is performed on the basis of the process model. Thus, another simulation variable is defined as the structure matrix D according to the resource link. In addition, the state of machining equipment greatly affects the manufacturing process. For example, the production could be broken down under condition of the machining equipment failure. A simulation variable is expressed as the state vector $DS = [ds_1, ds_2, \ldots\ldots, ds_n]$, where ds_n shows the machining equipments state. When a machining equipment is useful, ds_n is equal to "1."

The structure matrix D_k is defined as $D_k = (d_{i\times j})_{m\times n}$, where m is the number of resource node SD, n is the number of functional node FD, and k is the number of submodel. The element $d_{i\times j}$ is determined according to the connection relationship between the functional node FD and the resource node SD. Under condition that the direction of resource link is from the resource node SD to the functional node FD, the element $d_{i\times j}$ is set to "-1." Instead, the element value is "1." The value "0" means that no relationship exists between two nodes. The structure matrix D_k can be determinate according to submodels, and the structure matrix D_k can be automatically reconstructed through logical inference under condition of the alteration of process procedure. For a machining equipment, there exists a certain manufacturing cycle, so the manufacturing cycle function can be expressed as a discrete-time sequence function. Through the integration, the discrete-time sequence schematics can be obtained. The resource vector RS_t at any time t can be evaluated by the following equation:

$$RS_t = RS_{t-1} + \sum_{i=1}^{n} D_i \cdot DS_i, \tag{3}$$

where the resource vector RS is define as $[w_1, w_2, \ldots, w_n]$, in which w is the power value of resource link and n is the number of resource node. Through (3), production state at any time t can be obtained. Therefore, manufacturing process can be expressed dynamically. For other departments, more attentions are paid to the manufacturing time and cost. According to the components of process model, the time/cost estimation can be performed by defining related simulation variables, which is not discussed in this paper.

5 Case Study

A part is taken as an example to explain the process modeling and simulation. Its manufacturing process is listed in Table 1.

Machining equipments include a lathe (L_1), a drilling press (D_1), and a milling machine (M_1). The predicate logic representation of process procedure is expressed as follows:

TABLE 1
List of Process

No.	Machining method	Equipments
N1	Drill or mill hole	D_1 or M_1
N2	Mill surface	M_1
N3	Lathe surface	L_1

1. $Pro\text{-}Drilling(FD_1, SD_1, ID_1) \vee Pro\text{-}Milling(FD_2, SD_2, ID_1)$;
2. $Pro\text{-}Milling(FD_2, SD_2, ID_2)$;
3. $Pro\text{-}Lathing(FD_3, SD_3, ID_3)$.

Inference process is expressed as follows:

1. $Pro\text{-}Drilling(FD_1, SD_1, ID_1) \vee Pro\text{-}Milling(FD_2, SD_2, ID_1) \rightarrow Node\text{-}Connection(ID_1, FD_1) \wedge Node\text{-}Connection(SD_1, FD_1) \wedge Node\text{-}Connection(SD_1, FD_2)$;
2. $Pro\text{-}Milling(FD_2, SD_2, ID_2) \rightarrow Node\text{-}Connection(ID_2, FD_2) \wedge Node\text{-}Connection(SD_2, FD_2)$;
3. $Pro\text{-}Lathing(FS_3, SS_3, IS_3) \rightarrow Node\text{-}Connection(IS_3, FS_3) \wedge\ Node\text{-}Connection(SS_3, FS_3)$;
4. $(Pro\text{-}Drilling(FD_1, SD_1, ID_1) \vee Pro\text{-}Milling(FD_2, SD_2, ID_1)) \vee Pro\text{-}Milling(FD_2, SD_2, ID_2) \rightarrow Node\text{-}Connection (ID_1, FD_2) \vee\ Node\text{-}Connection(FD_1, SD_2)$;
5. $Pro\text{-}Milling(FD_2, SD_2, ID_2) \vee Pro\text{-}Lathing(FD_3, SD_3, ID_3) \rightarrow Node\text{-}Connection(FD_2, SD_3)$.

Combination of the inference results can construct all submodels. Consequently, the process model is constructed by integrating all submodels, as shown in Fig. 2.

According to above submodels, the structure matrix D_i and state vector DS_i are, respectively, obtained. Meanwhile, the discrete-time sequence schematics can be obtained. In this example, the manufacturing cycle of drill press (D_1), milling machine (M_1), and lathe (L_1) is, respectively, 2, 5, and 7 seconds.

$$D_1 = \begin{bmatrix} -1 & -1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix},\ D_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 1 & 0 \end{bmatrix},\ D_3 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix},$$

$$DS_1 = [1 \quad 1 \quad 0]^T,\ DS_2 = [0 \quad 1 \quad 0]^T,\ DS_3 = [0 \quad 0 \quad 1]^T.$$

Under the condition of the initial resource vector $RS_0 = [6\ 0\ 0]^T$, the resource vector RS_1 is calculated at time $t = 2$:

$$RS_1 = RS_0 + \sum_{i=1}^{3} D_i \cdot DS_i = RS_0 + D_1 \cdot DS_1 = \begin{pmatrix} 6 \\ 0 \\ 0 \end{pmatrix} + \begin{bmatrix} -1 & -1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 4 \\ 2 \\ 0 \end{pmatrix}.$$

The resource vector RS_2 at time $t = 4$ is obtained by the following equation:

$$RS_2 = RS_1 + \sum_{i=1}^{3} D_i \cdot DS_i = RS_1 + D_1 \cdot DS_1 = \begin{pmatrix} 4 \\ 2 \\ 0 \end{pmatrix} + \begin{bmatrix} -1 & -1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 2 \\ 4 \\ 0 \end{pmatrix}.$$

Finally, all resource vector RS_i can be obtained, as listed in Table 2.

In order to evaluate manufacturing performances, above calculation results are plotted, as shown in Fig. 3. From above figures, the following conclusions can be drawn.

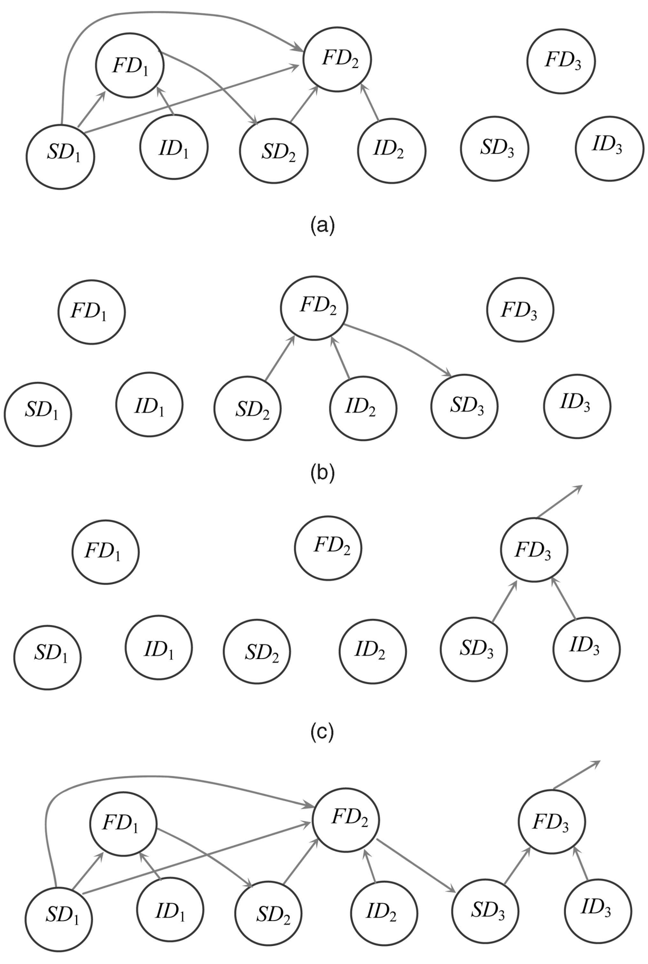

Fig. 2. Submodels and process model. (a) Submodel 1. (b) Submodel 2. (c) Submodel 3. (d) Process model.

The utilization rate of drilling press, milling machine, and lathe is, respectively, 22.2, 83.3, and 38.9 percent. Therefore, more maintenance should be given to the milling machine, and improvements should be made for the drilling press and lathe. The drilling press remains idle over time range of $t = 6\text{-}56$, and the maximum value occurs at time $t = 0$; the lathe is idle during time $t = 0\text{-}6$.

The production efficiency can be evaluated by the slope of fitted curve. The bigger the slope is, the higher the production

TABLE 2
List of Resource Vector RS

Time	0	2	4
Result	(6,0,0)	(4,2,0)	(2,4,0)
Time	5	6	7
Result	(2,3,1)	(0,5,1)	(0,5,0)
Time	10	14	20
Result	(0,4,1)	(0,4,0)	(0,3,1)
Time	21	28	30
Result	(0,3,0)	(0,3,0)	(0,2,1)
Time	35	40	42
Result	(0,2,0)	(0,1,1)	(0,1,0)
Time	49	50	56
Result	(0,1,0)	(0,0,1)	(0,0,0)

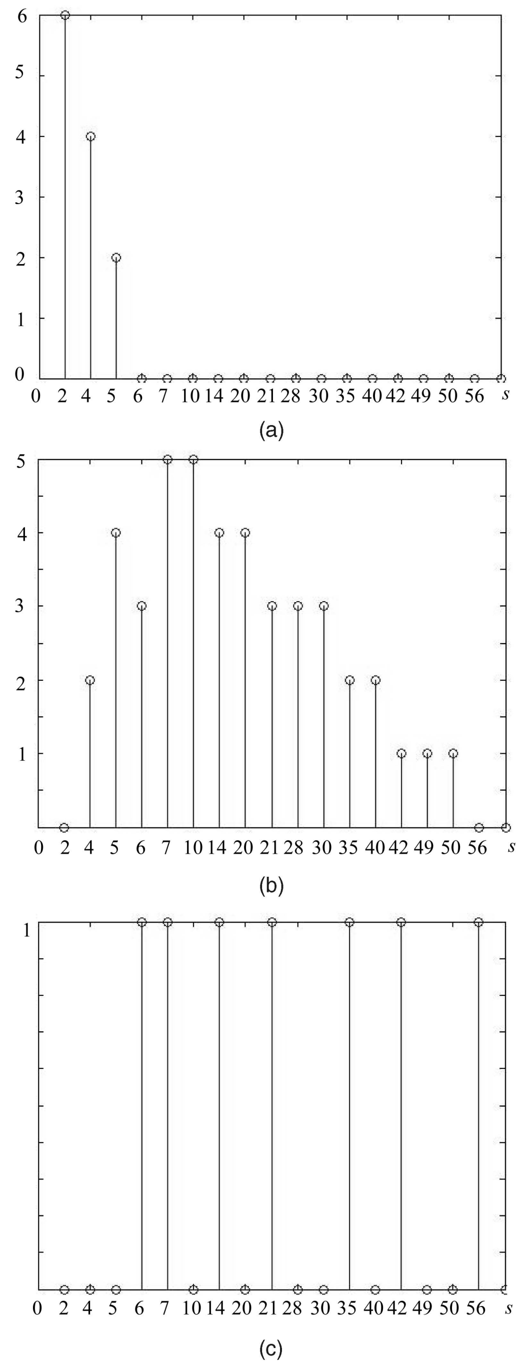

Fig. 3. Resource flow of machining equipments. (a) The resource flow of drilling press. (b) The resource flow of milling machine. (c) The resource flow of lathe.

efficiency is. The drilling press has high production efficiency at the earlier production. Then, the production efficiency decreases gradually. The production efficiency of lathe and milling machine fluctuates obviously. Therefore, more attentions should be paid to lathe and milling machine in order to guarantee the stable production efficiency.

The workload of drilling press is heavy at the earlier stage of production. Milling machine is subjected to the heavy workload at the end of production. The workload of drill press fluctuates placidly. Therefore, more assistance should be given to the milling machine and drill press.

In order to analyze the bottleneck of manufacturing process, the subtraction between the resource amounts of machining equipments is performed. For the lathe and drill press, the negative value occurs over the range of $t \in [10\ 50]$, and the maximum value is located at the time $t = 20$. Therefore, the production bottleneck between the lathe and drill press occurs at the time of $t = 20$. The probability of production jam is about $40/56 \times 100\ \text{percent} = 71\ \text{percent}$. In the same way, the negative value lies in the rage of $t \in [12\ 56]$ and $t \in [16\ 40]$ for the drill press and milling machine, and the maximum values, respectively, appear at the time of $t = 24$ and $t = 35$. Moreover, the probability of production jam is about $24/56 \times 100\ \text{percent} = 42.8\ \text{percent}$. From the collection results, the maximum value for the lathe and the drill press is much bigger than that of between the drill press and milling machine. Therefore, the production jam of the former is much heavier than that of the latter. Therefore, more improvements should be made to the lathe and the drill press.

6 Conclusions

The manufacturing process is under the control of process procedure. Therefore, process procedure has a great and important effect on the manufacturing process. Generally, the format of process procedure is regular and process information is clear. The process procedure is applicably expressed as a series of knowledge. Thus, the logical inference can be applied to construct the manufacturing process model. Process procedure includes two components—manufacturing behavior and manufacturing information. These components can be mapped into the predicate and variables, and process procedure can be expressed as a series of predicate formulas. Moreover, a modeling element presented in this paper is related to machining equipment, machining requirement, and raw material. Under the condition of single production pattern, five basic inference rules are lay down to construct the process model. According to the process item, the predicate formulas are obtained. The logic inference of single predicate formula and between adjacent predicate formulas is performed to construct related submodel. All submodels can be integrated into the process model. On the basis of the process model, the structure matrix, state vector, and resource vector are defined, respectively. Thus, the simulation algorithm of manufacturing process is determined. Manufacturing performances can be evaluated, such as the production efficiency and production bottleneck. Above all, the method proposed in this paper realizes the intelligent modeling of manufacturing process and the evaluation of manufacturing behaviors.

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