Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2008
August 3-6, 2008, Brooklyn, New York, USA

DETC2008-49170

DYNAMIC MODEL OF PROCESS PLANNING FOR TOP-DOWN COLLABORATIVE ASSEMBLY DESIGN

Youdong Yang
State Key Lab of CAD&CG
Zhejiang University
Hangzhou, 310027, P.R.China
(Ph: 086-571-87951045)
yyoudong@cad.zju.edu.cn

Shuting Zhang
State Key Lab of CAD&CG
Zhejiang University
Hangzhou, 310027, P.R.China
(Ph: 086-571-87951045)
zhangshuting@cad.zju.edu.cn

Zhihua Li
State Key Lab of CAD&CG
Zhejiang University
Hangzhou, 310027, P.R.China
(Ph: 086-571-87951045)
d98lzh@263.net

ABSTRACT

The design process of top-down collaborative assembly design is high parallel. There are complex task relationships not only in a task group but also among different task groups, which we call them as inside and outside relationships. A dynamic model of process planning based on hierarchical object-oriented Petri-net (HOOPN) is constructed for top-down collaborative assembly design. The dynamic model represents the outside and inside task relationships including parallel, sequential and coupling relationships. Based on the dynamic model, the dynamic supervising, analysis and decision-making for the states of the design process are implemented. The fuzzy overall evaluation model (FOEM) is utilized for risk evaluation of the design process. The task execution is influenced by local and global risk level from FOEM. Finally, the whole process planning is adjusted and controlled dynamically by the special risk decision-making mechanism.

Key Words: Process planning, Dynamic model, Dynamic supervision, Risk evaluation

1 INTRODUCTION

The assembly design is the main and key phase of new product development, and takes up a majority of development time. Top-down collaborative design could shorten product development cycle and improve design efficiency [1]. Top-down collaborative assembly design is composed of many tasks which are performed by distributed collaborators, and is high parallel. It is widely agreed that the design process includes requirements analysis, conceptual design and detailed design. When the concept design is finished during the design process, the main task of designers is to collaboratively accomplish the assembly design. This is shown in figure 1 which starts with product concept model and goes through an iterative process of layout design, skeleton design and detailed design[2].

1. Layout design. It is the design stage during which the abstract specification of the product is created containing the critical elements such as the key subassemblies and parts, the main assembly relationship and functional and structural constrains of the product. Based on the abstract specification of the product, the chairman assigns the subassemblies and parts to different designers according to the human resource.

2. Skeleton design. It is the design stage during which the 3D skeleton assembly model is created collaboratively by the designers undertaking different subassemblies or parts. The 3D skeleton assembly model contains product information such as the overall shapes and container spaces of the subassemblies and key parts, the assembly relationship specifications and key assembly constraints and some key parameters and so on.

3. Detailed design. At this design stage, the final assembly model is established collaboratively by the designers consisting of the detail geometric model and assembly relationships with geometric constraints and parametric constraints.

The information of the whole design process is imperfect and uncertain, and can't entirely be open to all. So the top-down collaborative assembly design process is parallel and complex, and there are complex task relationships not only in a task group but also among different task groups, which we call them as inside and outside relationships. Based on the characteristics of top-down collaborative assembly design, the product development process needs effective planning and management to guarantee the development cycle and design efficiency.

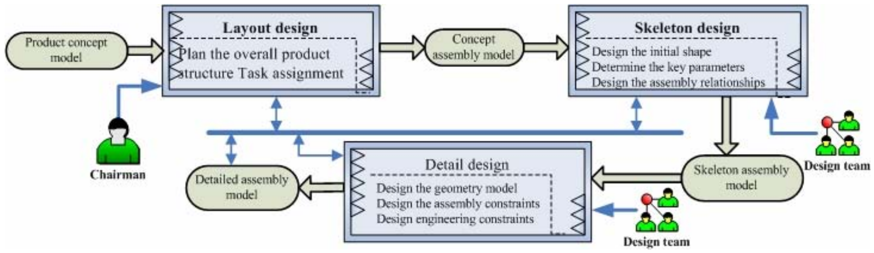

Fig.1. The top-down collaborative assembly design process

Before the top-down collaborative assembly design process starts, the whole tasks are grouped into several groups, and then the task groups are assigned to right design teams [3].Two task grouping principles are adopted: one is high coupling relationship tasks in the same task group and the other is workload equilibrium of the design teams. That can reduce coupling degree among task groups, effectively decrease interaction between design teams, and guarantee that the design process is high parallel and the cooperating complexity is reduced. Then the design process static planning should be determined after the task assignation finish. Because there are many task relationships of outside and inside task groups, the information of the whole design process is incomplete and uncertain, and can't be opened entirely, the static planning only can instruct the whole design process, but can't reflect the dynamic practice design process of development. The designer couldn't guarantee the design process to be executed according to a preceding statistic work-flow [4]. To guarantee the design process implementation and ensure the development cycle, we should supervise the states of every design groups, manage the process dynamically, make decisions based on the current process states, and adjust the time windows of the tasks and the development schedule of the project dynamically. So the dynamic model of process planning, analysis of dynamic influence factors, supervision, risk evaluation and decision-making are key issues to implement dynamic process planning.

In this paper, HOOPN is adopted to construct the dynamic model of process planning for the top-down collaborative assembly design. The models of the outside and inside task relationships among the task groups are constructed through Petri-net. In order to implement dynamic process planning, the model of dynamic supervision is added to the model of the design process. The complex model is subdivided using shadow place and transition so that the model of design process can be constructed automatically based on Design Structure Matrix (DSM). To adjust and control the process planning of top-down collaborative assembly design, the FEOM algorithm is applied for risk evaluation, and then the adjusting decisions of process planning are made based on the risk level of design process.

The remaining of the paper is organized as follows: Section 2 describes related works. The definitions of related Petri-net are given in section 3. Section 4 and section 5 describe the model of the design process sub-net and the model of the dynamic supervision sub-net. The dynamic model of process planning based on HOOPN and risk decision-making mechanism are discussed in section 6. Finally, the application of our model and algorithm is given in section 7.

2 RELATED WORKS

There are many researches on collaborative design process planning. PARK and CUTKOSKY [5] use a modeling method named Design Roadmap (DR) to construct framework for modeling dependencies in collaborative engineering processes. WANG and JIN [6] present a new modeling dependency in engineering design which integrates design units, design tasks and design recourses. TANG and ZHENG et a1. [7] use Directed Diagram (DD) and Design Structure Matrix (DSM) to describe relationships of design activities, and present reengineering of the design process for concurrent engineering. The DSM provides a dominant way to describe relationships of design activities [3, 7-9]. Zhu Yaoqin and Tian Feng et al. [10, 11] research on collaborative controlling mechanism & its application based on distributed Petri-nets. Zhou Xionghui et al. [12] study on coupling among design tasks. The tasks are grouped according to the coupling degree among them. The methods mentioned above are suitable for constructing model, planning and static relationships of design process in static condition, but hardly describe the dynamic design process in high parallel and existing constrains among outside and inside task groups conditions.

3 HIERARCHICAL OBJECT-ORIENTED PETRI-NET (HOOPN)

The Petri-net is a formal modeling language for describing and studying parallel information processing systems. The generality of its representation leads to a wide variety of applications. Object-oriented Petri-net (OOPN) is an advanced Petri-net. The elements of it are systemized as objects, i.e. are provided with attributes and methods. HOOPN is a special Petri-net that imported the hierarchical idea into OOOPN [13]. HOOPN-based model is simple, intuitive and hierarchical. The issues that Petri-net model tends to become too large for analysis even for a modest-size system are resolved.

Definition 1: HOOPN=(P,T,F,M0,Q,G,H,IN,OUT,R), where $P=\{p_1,p_2,\ldots,p_m\}$ is the set of object places, $T=\{t_1,t_2,\ldots,t_m\}$ is the set of object transitions satisfying $P \cap T=\phi$, Q ={SCPN, PAPN } is the transition set which is the set of sub-nets, SCPN is a HOOPN model, namely sub-net of supervision, PAPN$=\cup$EOOPN is the set of design process sub-nets, $F=\{T\times P\}\cup\{P\times T\}\cup\{Q\times T\}\cup\{T\times Q\}\cup\{Q \times P\}\cup\{P\times Q\}$ is the set of arcs, $IN=\{in_1,in_2,\ldots\}$ is the set of input places of sub-nets, and $OUT=\{out_1,out_2,\ldots\}$ is the set of output places of sub-nets; M_0 is the initial state mark, $R=\{r_1,r_2,\ldots\}$ is the relationship set among PAPN, and r_i describes the relationship among activities.

Definition 2: OOPN={P,T,F,M_0}, where P={p_1,p_2,…,p_m} is the set of all object places, T={t_1,t_2,…,t_m} is the set of all object transitions satisfying $P\cap T=\phi$; $F=\{T\times P\}\cup\{P\times T\}$ is the set of arcs, M_0 is the initial state mark.

Definition 3: EOOPN is the extended OOPN, EOOPN=｛P,T,OP,IP,ET,F,OF,IF,M0｝, P={p_1,p_2,…,p_m} is the set of all object places, T={t_1,t_2,…,t_m} is the set of all object transitions, OP={op_1,op_2,…,op_i} is the set of output places, IP={ip_1,ip_2,…,ip_n} is the set of input places, ET={et1,et_2,…,et_k} is the set of exterior transitions, and $P\cap T\cap IP\cap ET\cap OP=\phi$, $F=\{T\times P\}\cup\{P\times T\}$ is set of arcs, OF=｛T×OP｝is the set of output arcs, M_0 is the initial state mark.

Definition 4: Shadow place/transition is the input place/transition of the Petri-net model in order to reflect the relationships among process sub-nets model, and has the same attributes and states of the output place.

Output and input places, exterior transitions reflect the relationships among process sub-nets, and each input place is the shadow of the output place. Exterior transition is a shadow transition derived from a process sub-set which associates with its process sub-set. The shadow place/transition replaces the connecting arcs among sub-nets which describe the relationships of sub-net, and can subdivide the whole model into sub-models. The complexity of the net system is greatly reduced and the readability is improved based on the shadow place/transition. So it is easy to construct and independently denote the sub-sets.

4 DESIGN PROCESS SUB-NET MODEL BASED ON DSM AND EOOPN

4.1 PETRI-NET MODELS OF OUTSIDE AND INSIDE TASK RELATIONSHIPS

Before the top-down collaborative assembly design process, the whole tasks are grouped into several groups, and then the task groups are assigned to suitable design teams. So there are two kinds of relationships among design tasks: outside and inside task groups. The outside relationships mean the task relationships among the design teams, and the inside relationships mean the relationships among tasks in the same design tasks. For the inside relationships among tasks, we only need to construct sequence model and parallel model, and needn't consider coupling relationship since coupling tasks need to be combined into one task according to requirements of dynamic planning. For the outside relationships among tasks, there are only sequence model and coupling model need to be described, and we needn't consider parallel relationship because the parallel task among task groups is independent to each other. Two preconditions exist in our approach: one is that the execution of a task couldn't be interrupt once it's fired and the other is that the human resources in one design group can't be preempted.

(1). The Models of Inside Relationships

The tasks in the same task group are achieved according to the sequence by a design group because the task group can not be subdivided. The coupling tasks are combined as one task in the same task group so that there are two kinds of task relationships, i.e. the parallel and sequence relationships.

Conventionally, places are drawn as circles, and the transitions are drawn as rectangles. Figure 2 shows the model of sequence relationship, the transition t_j has the possibility to be fired after transition t_i is completed.

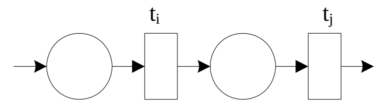

Fig.2. The model of sequence relationship

The parallel relationship model is shown as figure 3. Suppose there are two parallel tasks in the same design group, task p_i and task p_j. They have the same possibility to be fired at the same time, but only one can be fired because there has only one design group and the other one has to wait till the design resource release. Just one of the transition t_i and t_j can be fired and it is an uncertain choice. In this paper we add a process controlling place p_{cp}(see figure 3) to solve this question. Suppose the transition t_i is fired firstly, and t_j can't be fired. Two tokens are produced after t_i completed, one token denotes that t_i has been completed, and the other token is delivered to place p_{cp}, and t_j can be fired. In order to prevent t_i from being re-fired, we append a suppression arc (line with a little cycle at the end) in its successor place. The transition t_i can't be fired when its successor place with suppression arc has token. The successor transition hasn't the possibility to be fired until t_i and t_j both completed. If both of them were in the state of activating possibility, the key task should preempt the firing token.

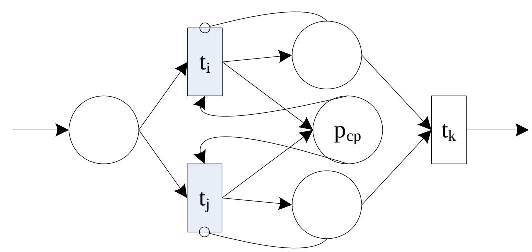

Fig.3. The parallel relationship model

(2). The Models of Outside Relationships

In order to reduce the complexity of the design process models, the shadow place and transition are adopted to describe the model based on the definition of EOOPN (Definition 2).

Figure 4 shows the model of sequence relationship between two task groups. Transition t_{ni} and t_{mj} belong to the *n-th* and *m-th* sub-process, and t_{ni} is the preceding transition of t_{ni}. t_{mj} has the firing possibility only when the place p_{ij} has token (figure 4 (a)). ps_{ij} (dashed cycle) is the shadow place of p_{ij} ($p_{ij}\in OP_n$, $ps_{ij}\in IP_m$) which cuts the link of two design sub-processes (figure 4(b)), and then change the model in figure 4(a) to the model in figure 4(b). That can effectively reduce the complexity of the whole system process.

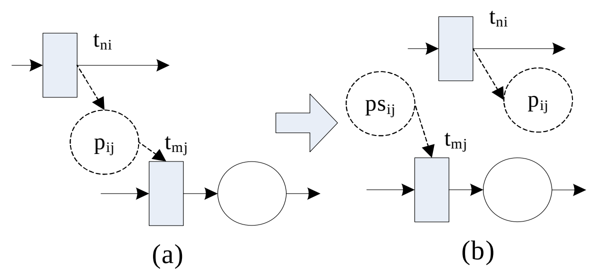

Fig.4. The model of sequence relationship among task groups

The model of coupling relationship among design processes is shown in figure 5. There are coupling relationship between transition t_{ni} and t_{mj}. The firing time of two transitions could be different, but none of them can be finished before the coupling contents between them completed. The switch arc (dashed line with ♀ at the end) is applied to describe this process (see figure 5). The successor place can't receive the token which is produced by the transition until the coupling process of the outside transition is completed, i.e. the switch arc unlocks when it meets the coupling information which the outside events required. The transitions tc_{mj} and tc_{ni} (dashed rectangle) are the shadow transitions of tm_i and tm_j which cut the link of two design sub-processes (figure 5(b)), and then change the model in figure 5(a) to the model in figure 5(b).

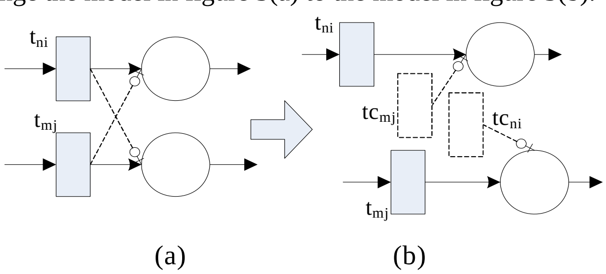

Fig.5. The model of coupling relationship among design processes

(3). The Model of Design Sub-process

The design sub-process models of top-down collaborative assembly design could be constructed according to the relationships among the tasks based on above contents.

Figure 6 shows a model of design sub-process. In this model, t_{51} has an output place $p54_{31}$ that denotes it has an outside successor t_{43}, t_{52} has an input shadow place $ps65_{35}$, which means it is the outside successor of t_{65}, tc_{23} is the shadow of t_{23} that denotes there is an outside coupling relationship between it and t_{52}. p_{cp} is a parallel control place which means there is an inside parallel relationship between t_{53} and t_{54}.

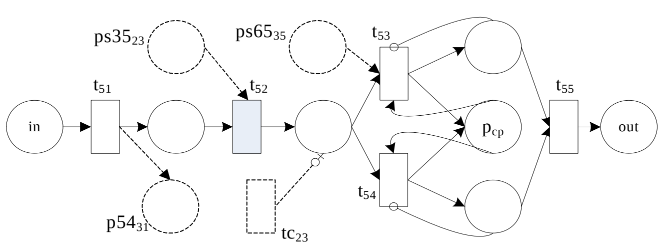

Fig.6. The model of design sub-process

4.2 THE OBJECT ATTRIBUTES OF MODEL ELEMENTS AND THE FIRING RULES OF TRANSITIONS

(1). The Element Attributes of Design Process Model

The element attributes of design process model should be setup according to the characteristics of dynamic design process planning for top-down collaborative assembly design. The design process sub-net model (PAPN) is an EOOPN model. The attributes of the transition, place, arc and token are provided in Table 1.

Table 1: The attributes of the transition, place, arc and token

element	attributes
Transition and shadow transition	ID, name, address, type, relationships, execution time window, start time, current time, workload, current finished workload, time window functions
Place and shadow place	ID, name, address, type
Arc	ID, name, type
Token	type, time

The ID and name of transition and place denote the number and the task name. The address is the memory address of the elements. The type is the description of different elements. The relationships record the outside and inside relationship among tasks. The execution time window represents the executing time scope of a task. The start time records the firing time of the transition. The current time denotes the current time of dynamic design process. The workload is the estimating time of the task design cycle. The current finished workload is the finished work of the task. The time window function is the function which calculates the execution time window of the tasks.

The shadow transition and shadow place are same as the hosts except for the attribute of the type. The attributes related to time denotes the date. Based on the time window functions and the time attributes of tokens, we could calculate the time windows of all tasks dynamically.

(2). The Firing Rules of Transitions

Each transition is connected to a number of input and output places. A transition may fire if all the input places contain enough tokens. Execution of a Petri net defines a sequence of events corresponding to the transition firings from the initial to a desired final marking. In this paper, the firing rules of transitions are shown as follows:

1) A transition may be fired if all the input places contain enough tokens except for the place with suppression arc.
2) A transition can't be fired if the input place with suppression arc has token.
3) A transition fire needs the inside preceding transitions to be finished because the task group which is done by one design group can not be subdivided.
4) A transition firing doesn't need the outside preceding transitions to be finished because its necessary

information of the outside preceding transition is achieved.

Based on the firing rules of transitions, the model of design process could be executed and satisfies the outside and inside relationship among tasks. If the active transition were the preceding item of a transition of outside design sub-process (sequence), a token should be produced and put into an output place while the necessary information of the successor transition achieved (the preceding events needn't be finished). The token is delivered to the sequence transition through the shadow place. The transition start time is determined through time window functions based on the time attributes of input tokens and equals to the maximum value of all tokens time. Based on the attributes and the firing rules of the Petri-net elements, the result of process planning could be obtained dynamically.

4.3 PETRI-NET MODEL OF DESIGN PROCESS SUB-NET

Top-down collaborative assembly design is composed of many tasks which are designed by distributed collaborators. There are many complex task relationships outside and inside task groups such that the modeling of design process sub-nets is very complex. DSM is one of the best models to describe the design task relationships. The DSM process model has good maneuverability and solidity since it has the advantages of easy implementation through computer program with no restrictions on task amount. But DSM doesn't have the capacity of the dynamic description. The combination of DSM and Petri-net integrates their advantages, and is convenient for constructing and analyzing Petri-net model of design process. In our paper, the expanded DSM is used to describe the relationships among tasks, and the design process Petri-net model could be automatically constructed using DSM. The relationship information of DSM is mapped to the Petri-net model. That can avoid manually building the Petri-net model which is a tedious work, and can guarantee the validity of it.

Definition 4: $A=(a_{ij})_{n\times n}$ is defined as the Relationship DSM (RDSM), n is the number of design tasks. $a_{ii}=0(i,\ j=1,2,...,n)$, the scope of a_{ij} value is $[0,1]$. $a_{ij}=0$ and $a_{ji}=0$, denotes that the relationship between task P_i and task P_j is parallel. $a_{ij}\neq 0,(0<a_{ij}\leq 1)$ and $a_{ji}=0$ denotes that the relationship between task P_i and task P_j is sequence, namely task P_i is the successor of task P_j or task P_j is preceding to task P_i. $a_{ij}\neq 0, a_{ji}\neq 0$ denotes that the relationship between task P_i and task P_j is coupling.

RDSM is an extended DSM, of which the element value denotes the task relationship degree. Due to the actual top-down collaborative assembly design process, two sequence tasks in different design groups are usually executed by different designers, so the successor does not need to wait until the preceding finish, and the coupling design tasks don't need to be completed at the same time. The sequential design activities could be paralleled and the coupling design activities could be sequenced so that product development cycle is reduced and the design efficiency is improved. If $a_{ij}\neq 0,(0<a_{ij}\leq 1)$ and $a_{ji}=0$, then the value of a_{ij} is the rate of workload, i.e. the successor has the firing possibility while the preceding could provide enough information. If $a_{ij}\neq 0, a_{ji}\neq 0$, then the value of a_{ij} and a_{ji} is the percentage of coupling design workload.

5 SUPERVISION PROCESS SUB-NET MODEL BASED ON OOPN

The supervision is to adjust and control the activity states of each design group dynamically during the top-down collaborative assembly design process. The supervision sub-net is a repeating process which receives and analyzes the current state information of the design process of all design groups continuously, and adjusts the design process according to the analyzing results. Since only one transition is active in one design sub-process currently, the information is changed along with the different transition firing. The supervision sub-net only receives information of active transition till the process finishes.

Figure 7 shows the dynamic supervision sub-net model. The transition *ts* is a supervision transition and can be refined. The place *ps* is the design process state place. The place *mt* is the supervision timing place. The whole design process doesn't need to be real-time monitored although the states of design process updates continuously. The place *mt* is a timer and produces token periodically, so the analysis of the whole design process is processed timely. The transition *ts* is fired while there are tokens in design process places and timing place. The result tokens are put into the place *psr*. The result tokens are delivered to every design process as decisions to adjust design process. The result tokens are instance of object with different adjustment information. In order to reduce the complexity of the model, the shadow place is applied. The place *pss* is the shadow of place *ps* and the *pssr* is the shadow of *psr* (see figure 7(b)). Here the shadow place only inherits one token which corresponds to it from host place.

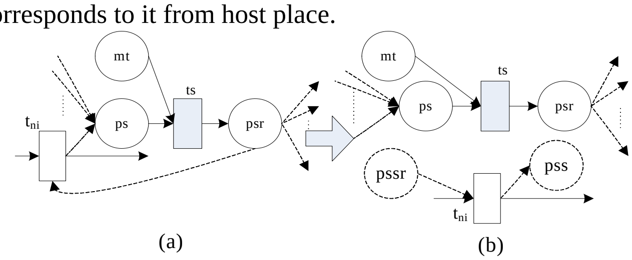

Fig.7. The dynamic supervision sub-net model

The Petri-net model of supervision sub-net is HOOPN, the transition *ts* is refined into design process supervision sub-net model (see figure 8). The refined model of *ts* can demonstrate its function in detail. The transition t_{re} is the risk evaluation activity and the transition t_{dm} is decision-making activity. The place p_{rl} is a risk level place. The elements of the monitor sub-net have object attributes respectively. The collaborative design process states are evaluated through the process supervision sub-net, and the risk level is calculated for local and global design process. The decisions are made according to the risk level, and issued to each design process to adjust the design process planning.

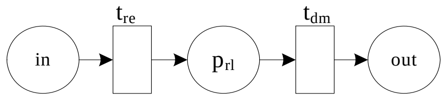

Fig.8. The Petri-net model of supervision sub-net

6 DYNAMIC MODEL OF PROCESS PLANNING BASED ON HOOPN FOR TOP-DOWN COLLABORATIVE ASSEMBLY DESIGN

6.1 DYNAMIC MODEL OF PROCESS PLANNING BASED ON HOOPN

The dynamic model of process planning based on HOOPN is shown as figure 9. The dynamic model can be refined and described hierarchically. Top-down collaborative assembly design process is started after the concept design is finished, and the key design tasks are determined. The task grouping and assignment should be done before collaborative assembly design. The design groups start design according to the static design process planning, and are managed dynamically during design process.

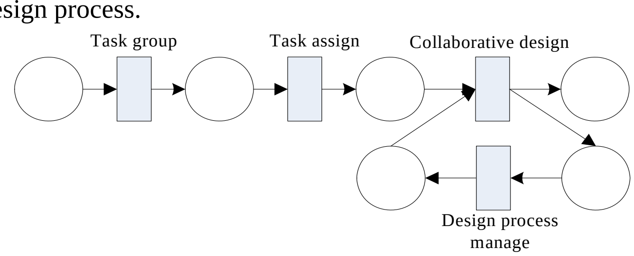

Fig.9. The model of process planning

In this paper, our main research is dynamic management for top-down collaborative assembly design process, and the management model of design process is shown as figure 10. The design process is refined into several design sub-processes, and the system model based on HOOPN is constructed.

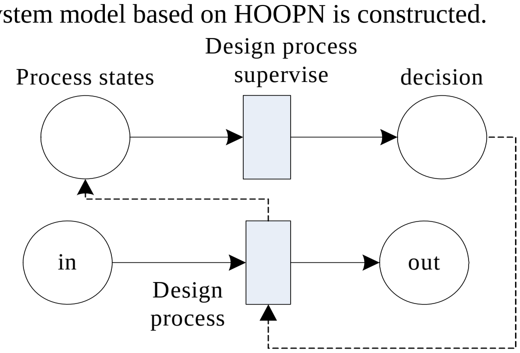

Fig.10. The management model of design process

Figure 11 shows the design processes sub-nets, the design process has *n* design groups which are associated with each other. We can describe the design sub-processes and supervision process independently since the shadow transitions and places are used. It is concise that the design process planning dynamic model is constructed based on the relationship models and process supervision model. During top-down collaborative assembly design process, since the design processes is refined and perfected continuously, the design process model needs to support the dynamic description capability. The HOOPN model is an open system, can describe the continuous refining design process based on the top-down process, and helps to effective manage of dynamic design process.

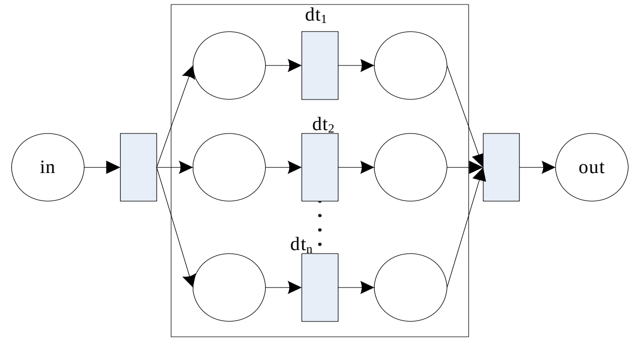

Fig.11. The design processes sub-nets

6.2 THE DYNAMIC RISK EVALUATION AND DECISION-MAKING

The dynamic progress of the project and the schedule of progress of cooperation objects are the key sectors which influence the design process planning. The stagnation of parallel sub-object (even if a small task) may influence the finish of the whole design project, especially for top-down collaborative assembly design. The static planning can't satisfy the requirements of dynamic management because static design process planning and design cycle are constructed based on experience estimation and the imperfection design information. In order to implement the dynamic design process management, the states of design groups should be supervised and analyzed, and the design process risk should be evaluated and decisions are made and put into effect according to the risk levels. So the dynamic progress of the project and the progress schedule of cooperation objects are realized.

The information of the design process states includes the current progress of every design groups, the states of the executing tasks, design model and the cooperation states. In this paper, the FOEM (fuzzy overall evaluation model) is applied for risk evaluation of design process [14].

The basic steps of FOEM are shown as follows:

Firstly, the critical factor set of an object is determined, i.e. all key factors of evaluation.

Secondly, the evaluation criterion or the remark set is constructed, and the factor weight set is constructed based on the assignment of the factor weights.

Thirdly, the evaluation and calculation of evaluation object are executed, and the evaluation matrix is constructed.

Finally, the evaluation result is gotten based on the fuzzy overall evaluation.

Suppose $U=\{ u_1,u_2,\ldots,u_n \}$ is the set of the critical factor, $V=\{V_1,V_2,\ldots,V_m\}$ is the set of evaluation, n and m are the number of them, and the number and the name of their elements are determined subjectively based on the fact. The evaluations are different due to their statuses, functions and weights of the critical factors. The overall evaluation set is a fuzzy sub-set of V since the values of the evaluation aren't Boolean values absolutely.

The critical factors of risk evaluation for top-down collaborative assembly design include the design progress, design model quality, the capacity of cooperation, design capability, the key degree of the task while each critical factor has its own weight. The evaluation specialists make risk evaluation of each design group according to the states of design process, and the risk membership of every critical factors are given for calculating the risk level.

The risk level calculating steps are as followed:

1) Fuzzy set construction. $U=\{ u_1,u_2,\ldots,u_n \}$, $i=1,2,\ldots,n$ is the critical factors set, n is the number of the critical factors, $V=\{V_1,V_2,\ldots,V_m\}$, $k=1,2,\ldots,m$ is the remark set, m is the number of remark levels.
2) Single factor evaluation. The risk membership of every critical factor is determined, namely a fuzzy mapping from set U to set V, and then we get the evaluation matrix R_i.

$$R_i = (r_{ijk})_{q\times m} = \begin{bmatrix} r_{i11} & r_{i11} & \cdots & r_{i1m} \\ r_{i21} & r_{i22} & \cdots & r_{i2m} \\ \cdots & \cdots & \cdots & \cdots \\ r_{iq1} & r_{iq2} & \cdots & r_{iqm} \end{bmatrix}, (i=1,2,\&,n)$$

, r_{ijk} denotes the V_k membership of u_{ij} critical factor.

3) The factor weight W_n determination.
4) Integrating evaluation.

$$B_i = W_i \times R_i = (b_{i1}, b_{i2}, \ldots, b_{im})$$

5) The evaluation result calculation. $b_i^* = \max(b_{i1}, b_{i2}, \ldots, b_{im})$, if $b_i^* = b_{ik}$, then $v_i^* = V_k$, i.e. the risk level v_i^* is obtained.

The design process risk evaluations of every design groups are calculated using above algorithm to get the risk level of design groups (local risk). The global risk is evaluated according to the local risk and key degree of the current design activities (as weight of factors).

The key degree of the design activity is determined through its influence on other activities which can be calculated through calculating the reachable matrix of the relationship DSM. The more activities that a task can reach, the more influence it has. The algorithm of reachable matrix could reference the paper [15].

The project needs to make decisions according risk level and main critical factors. If there are high local risk level and low global risk level, we only need to adjust the design process planning of the relevant design group. The whole project planning needs to be adjusted if the global risk level is high.

The design process risk level is divided into five levels, very low, low, middle, high and very high. There is no risk of design process while the risk level is 1 or 2. Some measures need to be adopted to reduce risk of design process (e.g. warning) while the risk level is middle. The design process is at the high risk and need to adjust the current state of it while the risk level is 4 or 5. The critical factor should be discovered that has the highest risk firstly, and the design processes are adjusted based on this factor. The adjustment decisions include re-planning, designer increase and designer exchange and so on. The risk of design process influences the schedule of product design ultimately, and consequently, the cycle of product development.

7 APPLICATIONS

To demonstrate the effectiveness of the proposed technique, we take the shaper design as an example. The design process includes 14 original design tasks, divided into four task groups, and the executing order of each task group is determined. The groups are showed as follows: the first group (t_4 crank and slider mechanism, t_1 cutter rest, t_2 slider, t_3 slider control set), the second group (t_8 cam mechanism, t_5 transverse feed mechanism, t_7 four-rod structure, t_6 ratchet wheel, t_5 parallel to t_7), the third group (t_9 workbench, t_{10} up and down control mechanism, t_{11} workbench frame), the fourth group (t_{12} driver set, t_{13} gear reducer, t_{14} lathe bed). The RDSM of the shaper design task is shown as figure 12.

In figure 12, the parallel, sequence and coupling relationships among design tasks of the shaper is described. Now, we take the second group as example to demonstrate how to construct the design process sub-net model.

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14
t1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t2	0.6	0	0	0.5	0	0	0	0	0	0	0	0	0	0
t3	0	0.7	0	3	0	0	0	0	0.5	0	0	0	0	0.2
t4	0	0	0	0	0	0	0	0	0	0	0	0	0.47	0
t5	0	0	0	0	0	0.2	0	0	0.56	0	0	0	0	0
t6	0	0	0	0	0.33	0	0.7	0	0	0	0	0	0	0
t7	0	0	0	0	0	0	0	0.5	0	0	0	0	0	0
t8	0	0	0	0	0	0	0	0	0	0	0	0	0.47	0
t9	0	0	0	0	0.44	0	0	0	0	0	0	0	0	0
t10	0	0	0	0	0	0	0	0	0.7	0	0	0	0	0
t11	0	0	0	0	0.5	0	0	0	0.8	0.7	0	0	0	0.2
t12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t13	0	0	0	0	0	0	0	0	0	0	0	0.4	0	0
t14	0	0.4	0	0.43	0	0	0	0	0	0	0.27	0.75	0.2	0

Fig. 12. The RDSM of the shaper design task

Based on the RDSM, the outside relationships of the second group are shown as follows: t_{13} is the preceding item of t_8, t_5 and t_9 is coupling and the preceding items of t_{11}. Figure 13 shows the EOOPN model of the second group. Each transition of figure should have an output place and an input shadow place which related to the supervision sub-net, here we omit them. The Process planning dynamic model of the shaper design based on HOOPN for top-down collaborative assembly design could be constructed through utilization of RDSM automatically and doesn't be given here.

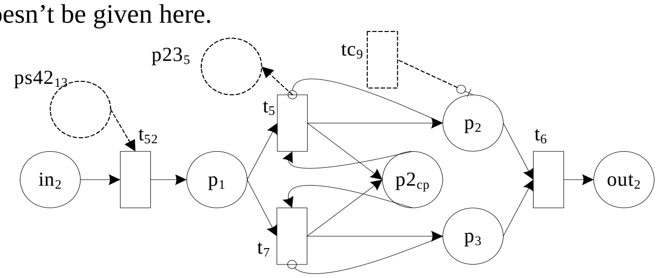

Fig. 13. The EOOPN model of the second group

Now, suppose the current active tasks are t_4, t_8, t_9 and t_{13}, and the states of the design process are delivered to the supervision sector. The risks of the design process are evaluated by specialists, and the decisions are made according to the risk level of it. Based on FOEM algorithm, the process is shown as follows.

Firstly, fuzzy sets U and V are constructed. The critical factors $U=\{ u_1, u_2, u_3, u_4, u_5 \}$: the design progress u_1, design model quality u_2, the capacity of cooperation u_3, design capability u_4, the key degree of the task u_5. The evaluation risk level V=(1,2,3,4,5). Based on the characteristics of design process, the critical factors weight W=(0.24,0.18,0.2,0.16,0.22) is determined. Then we get the evaluation matrix R_i, i=1, 2, 3, 4.

$$R_1 = \begin{bmatrix} 0.027 & 0.219 & 0.551 & 0.150 & 0.053 \\ 0.075 & 0.316 & 0.299 & 0.235 & 0.075 \\ 0.086 & 0.086 & 0.556 & 0.196 & 0.075 \\ 0.080 & 0.206 & 0.484 & 0.180 & 0.050 \\ 0.064 & 0.144 & 0.412 & 0.337 & 0.043 \end{bmatrix}, R_2 = ..., R_3 = ..., R_4 = ...$$

And the integrating evaluation B_1 is calculated, $B_1 = W \times R_1 = (b_{11}, b_{12}, b_{13}, b_{14}, b_{15}) = (0.065, 0.191, 0.366, 0.12, 0.091)$. The maximum element of B_1 is b_{13}, i.e. $b_1^* = 0.366$ and $v_1^* = 3$. So the risk level of the first group is 3, the design group should receive a decision "warning" according to the risk decision-making. Here we give the global evaluation matrix R straightly.

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} 0.065 & 0.191 & 0.366 & 0.12 & 0.091 \\ 0.060 & 0.367 & 0.327 & 0.174 & 0.061 \\ 0.217 & 0.357 & 0.314 & 0.144 & 0.068 \\ 0.042 & 0.323 & 0.328 & 0.272 & 0.036 \end{bmatrix}$$

C=(0.125,0.208,0.25,0.417) is the weight of four groups that determined by the critical degree of four tasks. And the integrating evaluation B is calculated, $B = C \times R = (0.093, 0.323, 0.329, 0.301, 0.056)$. The maximum element of B is b_3, i.e. $b^* = 0.329$, $v^* = 3$. So the global risk is middle level. According to this condition, the whole design process planning does not need to be adjusted, but the supervision should be enhanced, especially for the fourth design group since t_{13} has great influence on the successors.

8 CONCLUSIONS AND FUTURE WORKS

In this paper, the dynamic HOOPN model of process planning for top-down collaborative assembly design has been constructed. The outside and inside task relationships among the task groups are well described by Petri-net models. The complex system model is subdivided utilizing shadow place and shadow transition, a hierarchical description model is realized, which enabled the complex HOOPN model to be built through utilization of RDSM automatically. The resolution of model complexity and state explosion makes the model readability intelligibility. The design process state is real-time supervised through integrating the process supervision sub-nets into system model. The dynamic influence factors and executing risks of process planning is determined, and the local and global risk of process planning is dynamically determined using FEOM. The process planning and the process schedule are adjusted and controlled dynamically through decision-making based on risk level. The HOOPN model of process planning satisfies the dynamic requirements of design process, and guarantees the design cycle.

The process planning model can successfully achieve the dynamic description of top-down collaborative assembly design process, but the design process state need to be analyzed by experience experts and the evaluating results are lack of veracity. As part of an ongoing development, we intend to develop an automatic risk evaluation and decision-making expert system.

ACKNOWLEDGMENTS

The authors are very grateful to the financial support from NSF of China (No. 60574061).

REFERENCES

[1] GAO Shuming, HE Fazhi. Survey of Distributed And Collaborative Design. Journal of Computer-aided Design & Computer Graphics, 2004, 16(2): 149-157.

[2]Zhang ST, Chen X, Gao SM, Yang YD, A framework for collaborative top-down assembly design, Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Las Vegas, Nevada, USA, September 4-7, 2007

[3]YANG Youdong, ZHANG Shuting, GAO Shuming. Task Planning for Top-Down Collaborative Assembly Design. International Working Group on CSCW in Design, 2006, 05: 734-739.

[4] STEWARD D.. Planning And Managing of The Design Systems, Proceedings of Portland International Conference on Management of Engineering and Technology, Portland 1991, 27-31.

[5] PARK H, CUTKOSKY M R. Framework for Modeling Dependencies In Collaborative Engineering Processes. Research in Engineering Design, 1999, 11(2): 84-102.

[6] WANG KI, JIN Y. Modeling Dependencies in Engineering Design [A]. Proceedings of the ASME Design Theory and Methodology Conference. Las Vegas, NV, USA: ASME Press, 1999.

[7] TANG D, ZHENG L., LI Z, et a1. . Reengineering of the Design Process for Concurrent Engineering. Computers & Industrial Engineering, 2000, 38(4): 479-491.

[8] SU Caimo, KE Yinglin. Task Planning and Decoupling Strategy for Collaborative Design. Computer Integrated Manufacturing Systems, 2006, 12(1): 21-26.

[9] CHU Chuncao, CHEN Shushan, ZHENG Pie. Project Scheduling Model Based on Dependency Structure Matrix. Computer Integrated Manufacturing Systems, 2006, 12(10): 1591-1595.

[10]ZHU Yaoqin, WU Huixhong, Yu Yongjia, et al. Collaborative Controlling Mechanism & Its Application Based on Distributed Petri Nets. Computer Integrated Manufacturing Systems, 2005, 11(1): 85-89.

[11]TIAN Feng，LI Renhou，ZHANG Jincheng. Modeling and Performance Evaluation of Collaborative Works Based on Timed Colored Petri Net. Journal of Xi-an Jiaotong University. 2006, 37(6): 560-564.

[12] ZHOU Xionghui, LI Xiang Ruan Xueyu. Study on Task Plan Algorithm for Injection Product and Mold Collaborative Design, Chinese Journal of Mechanical Engineering, 2003, 39(2): 113-118.

[13] HONG Jang-eui, BAE Doo-Hwan. Software Modeling and Analysis Using a Hierarchical Object-Oriented Petri Net. Information Sciences. 2000, 130(12, 1-4): 133-164.

[14] LI Yu-hua, LANG Hong-wen. Research on Fuzzy 0verall Evaluation Model for Investment Risks in High-tech Projects. Journal Harbin UNIV.SCI.＆ TECH. 2004, 9(1): 72－75.

[15] WNANG Hongwei. Modeling and Simulating. Beijing: Science Press, 2002, 41-51.