Collaborative design implementation on the PN-PDDP model for the complex coupled rotor systems

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Abstract: By considering what is necessary to implement a multi-component collaborative design process for a product, a PN-PDDP (Petri Nets for Performance Driven Design Process) model based on extended Petri nets is presented. In this paper the model is used to design a complex and multi-component high-speed turbopump rotor system for a liquid rocket engine. The study on the definitions of the features of the coupling design process, such as the sequence of concurrent activities, a reachability tree, a design cycle tree and design conflicts, are presented and the solving methods for these features are proposed. The computer simulation for these features by a self-programming emulating package is shown. The coupling design process for a specific multi-component high-speed turbopump is carried out, and the matrix for the coupling design process and software is developed. The results show that the PN-PDDP model based on the Petri network can effectively couple existing knowledge resources, solve any conflict arising from different knowledge, and achieve an optimal strategy for the performance driven design process.

Keywords: PN-PDDP model, petri nets, computer simulation, coupled design, knowledge resources.

1. INTRODUCTION

A past study has presented a PN-PDDP (Petri Network for Performance Driven Design Process) model based on extended Petri nets so as to enhance design efficiency and quality after analyzing the design process of a performance-driven multi-component coupling rotor system for a liquid rocket engine (Zhang et al, 2016). This defined the performance characteristics library, the characteristics feature library, the traces Token, and firing rules. However, solving methods for the model should be developed, and characteristics parameters should be created for the flow process of varied coupling information and also the performance-driven conflict solving mechanism when adopting the model, so as to meet the requirements of extant rules and feature library. To this end, the present study examines characteristics defining and parameter solving of the model. Computer simulation of the design process is used so as to provide a supporting tool and platform for the digital design and integration of the complex multi-component coupling rotor system (typified by the high-performance high-speed turbopumps).

There have been a number of studies which build Petri nets-based models with varied targets and proposed solving methods. For example, Fang et al. built an object-oriented colored Petri net mode for an automotive electronic system to solve its characteristic parameters (Fang et al, 2011). For a collaborative design system, HUANG H. Z. et al established temporal and resource coordination mechanisms based on Petri Nets, these offer strong support for the performance evaluation of the collaborative design (Huang et al, 2010). Salinas F.S et al proposed a control scheme to regulate the flying capacitor voltages and the output current by using a Petri net methodology (Salinas et al, 2016).

Considerable attention has also been given to the application of Petri nets to the full life cycle for designing and the manufacturing mechanical products, such as in the assembling and disassembling, manufacture, and design stages. For example, HSIEH F.S. investigates the disassembling sequence optimization strategy (Hsieh, 2008). ERDEN Z. developed a virtual prototype for the logical behavior of robot design with Discrete Event System Specification (DEVS) and Petri Net formalism (Erden, 2011). POPESCU C. et al. discussed how to automatically incorporate resources in a Petri-net-derived model of flow that is modifiable at runtime to reflect and influence the routing in a manufacturing line (Popescu et al, 2012). ISSAOUI L. et al. deals with automatic sequence generation for selective disassembly of mechanical product (Issaoui et al, 2015). BASAK O. et al. presented the design and the implementation of a Petri net (PN) model for the control of a flexible manufacturing system (FMS) (Başak & Albayrak, 2015). Luo Y. T. et al. introduced a method for the integration of multi-layer product representation and optimal searching in product selective disassembly planning (Luo et al, 2016).

With respect to modeling the design process with Petri nets, XU Q. L. et al. applied timed colored Petri nets (TCPN) to model various elements of the product variant design process (Xu & Jiao, 2009). KARNIEL A. et al. presented a formal translation of the DSM-based plan to a process-scheme model, the DSM net, which can be executed and simulated (Karniel & Reich, 2011); then, they also developed a multi-level modelling approach for supporting the management of evolving new product development (NPD) processes (Karniel & Reich, 2013). WANG T. R. et al. proposed a process planning framework, established a three-dimensional collaboration model, and analyzed nine collaboration types among activities (Wang et al, 2012). CHENG F. F. et al. presented the information constraint net (ICN) to represent the complex information constraint relations among design activities involved in the building design process (Cheng et al, 2013). ARAZ M. et al. focused on behavioural representation and simulation of design concepts via discrete event system specification formalism and Petri Nets (Araz & Erden, 2014).

These studies demonstrate the effectiveness of Petri nets in mechanical design or product design. Nonetheless, most of them concern particular projects and offer concrete results, and so far no study aims at a solving method for the multi-components collaborative design process. This study, therefore, sets out to obtain such a solving method so as to provide some guidance on conflict decoupling and collaborative design in a multi-source information coupling design process for the rotor system in a liquid rocket engine.

2. PETRI NETS MODEL FOR THE DESIGN PROCESS OF THE MULTI-COMPONENT HIGH-SPEED TURBOPUMP

Fig.1 presents the PN-PDDP model for the multi-component coupling turbopump rotor system in line with the definition of PN-PDDP. The whole design process for this model is introduced in our previous study (Zhang et al, 2016). Each symbol in Fig.1 is shown in Table 1 of the reference.

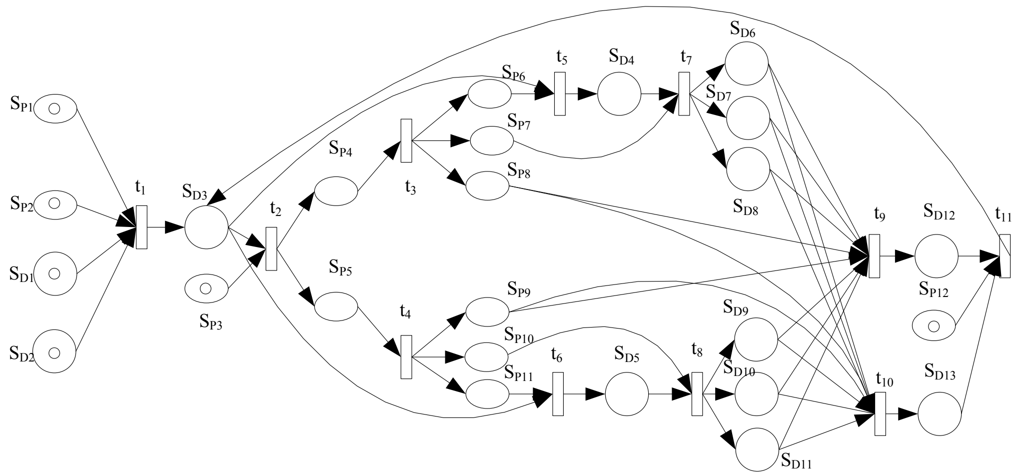

Fig.1. PN-PDDP for the multi-component coupling turbopump rotor system (Zhang et al, 2016)

Fig.1 shows the complex PN-PDDP design process where the design starts with the rotor's structure addressing a holistic requirements on the characteristic parameters of the rotor positioning and transmitting performance, the rotor system's components structure and the turbopump's shell structure parameters. This generates the rotor structure characteristics parameters. The bearing assembly is designed based on the load carrying needs of the rotational support, producing the radial and axial load carrying characteristics. Next, performance decomposition is achieved on radial multi-component coupling, thrust multi-component coupling, load capacity, and dynamics performance. The rotor and stator is then designed based on all these performance requirements. What follows is the design of the power amplifier controller and sensor according to the rotor and stator's structural characteristics and performance requirements. Finally, a dynamic check is made. If it does not meet the requirements, the process would iterate through revising the rotor's structural characteristics.

3. DETERMINATION OF CHARACTERISTICS PARAMETERS IN THE PN-PDDP

This section elaborates on the procedure for determining characteristics parameters and obtaining solving methods with the help of a simplified multi-component coupling rotor system design PN-PDDP model, as shown in Fig.2. The symbol and shape in Fig.2 are introduced in Table 1 of the reference (Zhang et al, 2016).

3.1 Correlation matrix

It is determined that the PN-PDDP includes the library set $S=\{s_1,s_2\cdots s_n\}$ and the activity set $T=\{t_1,t_2\cdots t_m\}$, and the matrix $C=\left\|c_{ij}\right\|(1\le i\le n,1\le j\le m)$ be the correlation matrix of the PN-PDDP, where,

$$c_{ij}=\begin{cases}1 & when, s_i\in t_j^{*}\\ -1 & when, s_i\in {}^{*}t_j\\ 0 & when, s_i\notin {}^{*}t_j\bigcup t_j^{*}\end{cases} \quad (1)$$

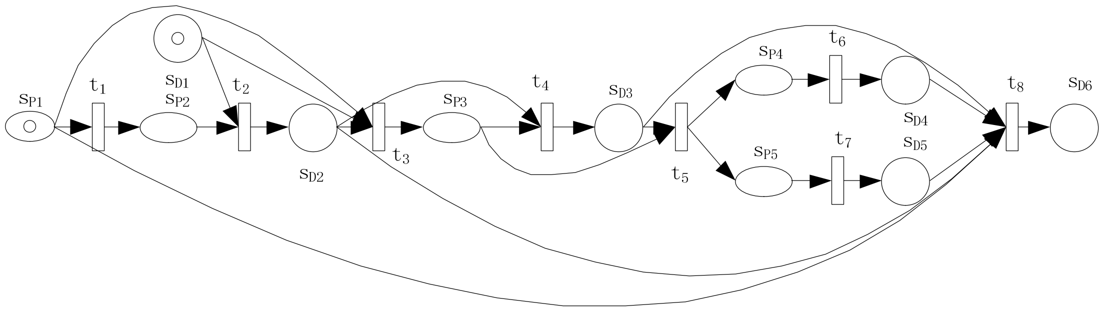

Fig.2. A simplified PN-PDDP model for a design process

The correlation matrix C of the aforementioned PN-PDDP model is shown as,

C =

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8
S_{P1}	-1	0	-1	0	0	0	0	-1
S_{P2}	1	-1	0	0	0	0	0	0
S_{P3}	0	0	1	-1	-1	0	0	0
S_{P4}	0	0	0	0	1	-1	0	0
S_{P5}	0	0	0	0	1	0	-1	0
S_{D1}	0	-1	-1	0	0	0	0	0
S_{D2}	0	1	-1	-1	0	0	0	-1
S_{D3}	0	0	0	1	-1	0	0	-1
S_{D4}	0	0	0	0	0	1	0	-1
S_{D5}	0	0	0	0	0	0	1	-1
S_{D6}	0	0	0	0	0	0	0	1

The correlation matrix describes the structure of the PN-PDDP, and obtains the characteristics of the design process.

3.2 Activity sequence

The state equation of the design process is as follows:

$$M_{Z+1} = M_Z + C'U_Z \tag{2}$$

Where, M_{Z+1} and M_Z are the two state labels in the design process, C' is the transformation matrix of the correlation matrix, and U_Z is the control vector. Because the PN-PDDP does not consider resource consumption as noted in the previous study (Zhang et al, 2016) , all the consumption elements (the elements with a minus sign) in the correlation matrix C are granted the value of 0, resulting in the transformation correlation matrix C' . U_Z corresponds to the activity transition set T , and is the process sequence of the design activity set of the Z stage. The element u_i in U_Z represents the frequency with which the transition t_i from M_Z to M_{Z+1} occurs.

The transformation correlation matrix C' of the above PN-PDDP in Fig.2 is in the following.

$$C' = \begin{bmatrix} 0&0&0&0&0&0&0&0 \\ 1&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&0 \\ 0&1&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0 \\ 0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1 \end{bmatrix}$$

Define $\sigma = M_0 t_1 M_1 t_2 \cdots t_n M_n$ as the activity sequence of the PN-PDDP, when it meets the condition of,

$$\forall i, 1 \le i \le n \Rightarrow M_{i-1}\left[t_i\right\rangle M_i$$

Where, $M_0, M_1 \cdots M_n$ representing varied intermediate stages (0,1,2,…,*n*). $M_{i-1}\left[t_i\right\rangle M_i$ indicates that when the library is in the state of M_{i-1} , activity t_i fires such that the library enters a new state M_i .

From Fig.4, the whole design process from its beginning to its end goes through the activity sequence of $\sigma = M_0 t_1 M_1 t_2 M_3 t_3 M_4 t_4 M_5 t_5 M_6 t_6 M_7 t_7 M_8 t_8 M_9$, where M_0 and M_9 signal the initial and the final state, respectively and $M_0 = \{1,0,0,0,0,1,0,0,0,0,0\}$, $M_9 = \{0,0,0,0,0,0,0,0,0,0,1\}$.

The activity sequence σ can be simplified as $\sigma = \{t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8\}$ if the activity sequence M is ignored.

Because each activity occurs just once, the control vector U_Z is the identity matrix I . As a result, the state equation of the entire design process can be captured as follows:

$$M_9 = M_0 + C'I \tag{3}$$

4. PN-PDDP CHARACTERISTICS

Regarding the multi-component collaborative design, the design process model manifests all characteristics of the design process, which are closely related to the successful execution and execution efficiency of the design process. The present study defines the major characteristics of PN-PDDP (concurrent design activities, design reachability, design cycle, design conflicts and so on), and solves the design process characteristics through the PN-PDDP characteristics parameters illustrated below.

4.1 Concurrent activity sequence

If two activities sequences σ_1 and σ_2 coincide with each other (signified as $\sigma_1 co \sigma_2$), then the following relationship exists:

$$\sigma_1 co \sigma_2 :\Leftrightarrow \sigma_1 \cap \sigma_2 = \Phi \wedge \neg(\sigma_1 < \sigma_2) \wedge \neg(\sigma_2 < \sigma_1)$$

Where, $<$ signals the interdependent relationship and the attendant sequential relationship between σ_1 and σ_2, that is, σ_1 occurs before σ_2. Fig.3 shows the concurrent activity sequence diagram of the model described in Fig.2.

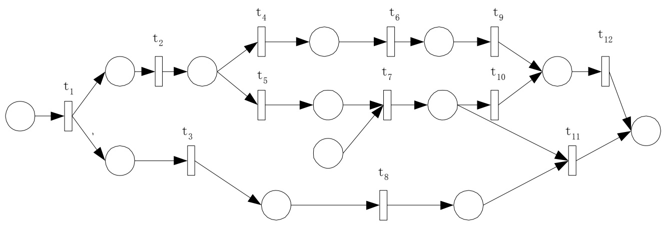

Fig.3. Concurrent activity sequence diagram

As shown in the above collaborative design PN-PDDP model, the activity sequences $\sigma_1 = \{t_4, t_6, t_9, t_{12}\}$ and $\sigma_2 = \{t_5, t_7, t_{10}, t_{12}\}$ meet the concurrent conditions such that they are called concurrent activity sequences.

In this study, the notion of concurrent rate is introduced to indicate the degree of concurrent activities in a design activity sequence, and is defined as the rate of the number of concurrent activities to the total number of activities in a design activity sequence. If R_c signals concurrent rate, the following formula obtains,

$$R_c(\sigma) = \frac{N_p}{N_\sigma} \quad (4)$$

Where, N_P is the number of concurrent activities and N_σ is the total number of design activities in the design activity sequence σ.

4.2 Design reachability

The design reachability in the PN-PDDP is meant to indicate that the set $[M_0\rangle$ is the minimal set meeting the following conditions:

(1) $M_0 \in [M_0\rangle$;

(2) If $M' \in [M_0\rangle, t \in T$, then $M'[t\rangle M$, resulting in $M \in M_0$.

The design reachability is used to verify whether the system could enter a certain state. In the PN-PDDP, reachability analysis is conducted to determine whether design performance and design data could be gained. Reachability analysis can be achieved through reachability trees, whose nodes indicate varied reachable states, and whose arcs represent events. The methods to create reachability trees can be referred to Reference(Chongyi, 2005). Fig.4 shows the reachability tree of the PN-PDDP in Fig.2.

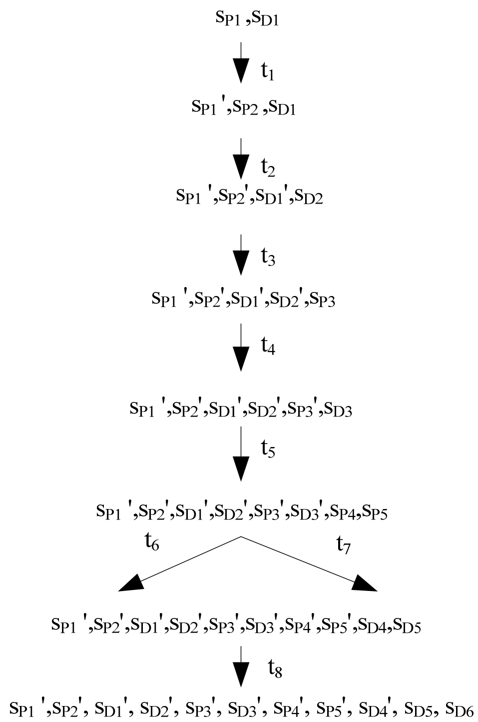

Fig.4. Reachability tree

As can be seen in Fig.4, the name of the library is used to indicate that it contains ordinary *Tokens*, and the name of the library together with the sign of ′ indicates that it contains trace *Tokens*. The reachability tree captures all the possible states represented by all the possible activities in the design process. Each activity and its node set contain all the possible design data which are gradually defined and added during the design process. If an activity in the design process is not included in the activity set, this activity is unlikely to occur; and if a data library is not included in the node set, the data is not liable to arise from the design process.

4.3 Design cycle

If the first and the last activities are the same in the activity sequence σ of the PN-PDDP, then this sequence is referred the design cycle. Fig.5 shows one example of a design cycle, in which the first and last activities of the activity sequence $\sigma_1 = (t_1, t_2, t_3, t_6, t_1)$ are the same. The design process is often too iterative. It is important to reduce number of interactions of the design activity cycle by identifying all design activities in the design cycle using the PN-PDDP and subsequently providing all possible design information to ensure high quality and first time right decision making.

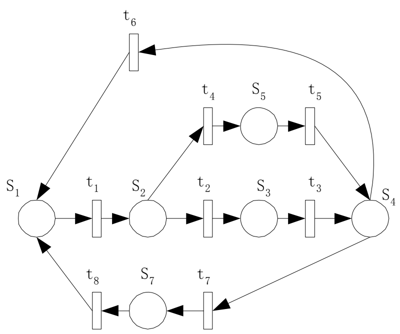

Fig.5. Diagram for the design cycle

4.4 Design conflicts

If two design activities t_i and t_j in the PN-PDDP have the relationship of $t_i^\bullet \cap t_j^\bullet \neq \varphi$, the two activities are said to have conflicts. That is, if two design activities in the design process attempt to modify either structure or performance characteristics data simultaneously, they are considered to have conflicts. For example, two design activities t_1 and t_2 modify the design data s_1 simultaneously, respectively such that they have access conflicts.

In multi-components collaborative design, conflicts are classified into two types according to which library is involved or where conflicts exist: namely performance conflicts and structure conflicts.

Performance conflicts occur in the performance decomposition process. If two preceding performance decomposition activities demand the same subsequent performance activity to ensure their respective performance, conflicts are said to have occurred in this subsequent performance activity. For instance, in the design of the complex multi-component coupling high-speed turbopump rotor system, maintaining the high-speed pumping performance of the pump system demands the rotor to achieve a certain rotation performance, and meanwhile, maintaining the dynamics performance of the rotor system also calls for the rotor to achieve a certain rotation performance. Consequently, the two aforementioned performance decomposition activities induce conflicts in the rotation performance activity. When performance conflicts occur, priority should be given to the issue of whether intersection exists between these performance characteristics. If it does, the intersection should be assigned as the value of performance characteristics so as to dissolve the conflicts. By contrast, if it does not, performance decomposition activities should be redone so as to dissolve conflicts either by maintaining the same scheme but generating an intersection between the performance characteristics or by choosing a different scheme so as to preempt the conflicts of the two preceding performance decomposition activities in the subsequence performance activity.

Structure conflicts occur in the detailed design process. If the same structure characteristic is required to meet two performance characteristics, conflicts can occur. For instance, in the design of the multi-component coupling rotor system, achieving the rotor’s transmission performance demands action on the shaft’s structure characteristics; meanwhile, achieving the shaft’s static and dynamic performance characteristics also demands action on the shaft’s structure characteristics. As a result, these three design activities (shaft’s structure design activity, rotor’s static design activity, and rotor’s dynamic design activity) will have conflicts in the shaft’s structure performance activity. The proposed structure conflicts resolution follows the following steps:

First, examine whether an intersection solution exists within the possible solution spaces of the conflicted structure requirements. If it does exist, the intersection should be assigned as the value of the structure characteristics. If it does not exist, the detailed design activity should be repeated with a view to create intersection between the solution spaces of the conflicted structure characteristics. If intersection still could not be obtained, the design performance requirements should be related and then decomposed again so as to redefine the performance characteristics of the design activity, which will allow design activities to proceed. In this way, structure conflicts are resolved.

From the above analysis of the PN-PDDP, finding conflicts in the design process and then resolving them could considerably enhance the design efficiency.

5. COMPUTER SIMULATION OF THE DESIGN PROCESS AND SOLVING METHODS FOR CHARACTERISTICS PARAMETERS

5.1 Solving method of concurrent activity sequence analysis

The following solving method could be worked out in terms of the definition of concurrent activity sequence. If library s is the before set of activity t_i and the after set of activity t_j , t_j is considered as the depending activity of activity t_i. All depending activities of t_i constitute its depending set.

(1) Search the activities which share the same depending set, and make them the concurrent activity set.

(2) Create the complete depending set of concurrent activities. If t_j is the depending activity of concurrent activities, t_j together with all its depending activities should be included in the complete set. That is, all the depending activities of concurrent activities coupled with their own

depending activities should be included in the final complete depending set.

(3) Search the activities which take the concurrent activity set and the complete depending set as their depending set, and accordingly creates their own concurrent activity set.

(4) Once all such activities have been included into concurrent activity sets, the activities of each concurrent activity set constitute an activity chain, called a concurrent activity chain.

5.2 Solving method of design cycle analysis

According to the Petri nets theory (Lohmann et al, 2009), the design cycle can be gained by solving the nonnegative constant $T\_$ of the PN-PDDP, which could be calculated by the following equation:

$$C \cdot J = \theta_s \tag{5}$$

Where, J is the constant $T\_$ of the PN-PDDP, C is the correlation matrix of the PN-PDDP, θ_s is the vector $S\_$ in which all elements have the value of 0.

5.3 Solving method of design conflicts analysis

The following procedure could be followed to search possible conflicts and relevant performance characteristics in terms of the above definition of design conflicts. Set the total number of all the libraries as m .

(1) Create the relevant matrix C .

(2) Set $i = 1$.

(3) Find the row in which library s_i in the correlation matrix C stays. Then find the columns in which elements in that row are of -1. Next find the activities that correspond to those columns, and those activities are the design activity set where conflicts are likely to occur in the library s_i , marked as T_i , $T_i = \{t_{i1}, t_{i2} \cdots t_{ik}\}$.

(4) Set $j = 1$.

(5) Find the column where t_{ij} lies in. Then find the performance libraries where corresponding elements in that column are of 1. Next, put those performance libraries into the conflict performance characteristics set P_i .

(6) If $j \langle k$, then jump to 4.

(7) If $i \langle m$, then jump to 2. Otherwise, the whole procedure is over.

6. SIMULATION SOLUTION AND IMPLEMENTATION FOR THE PN-PDDP MODEL

6.1 Concurrent activity sequence

The above solving method will be exemplified with the design of the multi-component coupling high-speed turbopump rotor system. Fig.1 shows the PN-PDDP of the multi-component coupling high-speed turbopump rotor system. Based on Eq. (1), its correlation matrix is shown as following,

$C^* =$

	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}
S_{P1}	1	0	0	0	0	0	0	0	0	0	0
S_{P2}	1	0	0	0	0	0	0	0	0	0	0
S_{P3}	0	1	0	0	0	0	0	0	0	0	-1
S_{P4}	0	-1	1	0	0	0	0	0	0	0	0
S_{P5}	0	-1	0	1	0	0	0	0	0	0	0
S_{P6}	0	0	-1	0	1	0	0	0	0	0	0
S_{P7}	0	0	-1	0	0	0	1	0	0	0	0
S_{P8}	0	0	-1	0	0	0	0	0	1	1	0
S_{P9}	0	0	0	-1	0	0	0	0	1	1	0
S_{P10}	0	0	0	-1	0	0	0	1	0	0	0
S_{P11}	0	0	0	-1	0	1	0	0	0	0	0
S_{P12}	0	0	0	0	0	0	0	0	0	0	1
S_{D1}	1	0	0	0	0	0	0	0	0	0	0
S_{D2}	1	0	0	0	0	0	0	0	0	0	0
S_{D3}	-1	1	0	0	1	1	0	0	0	0	0
S_{D4}	0	0	0	0	-1	0	1	0	0	0	0
S_{D5}	0	0	0	0	0	-1	0	1	0	0	0
S_{D6}	0	0	0	0	0	0	-1	0	1	1	0
S_{D7}	0	0	0	0	0	0	0	-1	1	1	0
S_{D8}	0	0	0	0	0	0	0	0	-1	-1	1
S_{D9}	0	0	0	0	0	0	0	0	0	0	1

(1) The depending sets of varied activities can be obtained through the relevant matrix, as shown in the following.

$D_{t1} = \{\varphi\}$; $D_{t2} = \{t_1, t_{11}\}$; $D_{t3} = \{t_2\}$; $D_{t4} = \{t_2\}$; $D_{t5} = \{t_3, t_1\}$; $D_{t6} = \{t_3, t_1\}$; $D_{t7} = \{t_3, t_5\}$; $D_{t8} = \{t_4, t_6\}$; $D_{t9} = \{t_3, t_4, t_7, t_8\}$; $D_{t10} = \{t_3, t_4, t_7, t_8\}$; $D_{t11} = \{t_9, t_{10}\}$;

(2) Find the activities with the same depending set, which in turn form the concurrent activity sets. As shown in the above depending set, D_{t3} and D_{t4} have the same depending set such that they constitute a pair of concurrent activity sets C_{11} and C_{12} , which all depend on the complete depending set of events DA_1 . That is, $C_{11} = \{t_3\}$, $C_{12} = \{t_4\}$, $DA_1 = \{t_1, t_2\}$.

(3) Include the activities, which take the concurrent activity set or complete depending set as their depending set, into the concurrent activity set in sequence.

$C_{11} = \{t_3, t_5\}$; $C_{12} = \{t_4, t_6\}$; $C_{11} = \{t_3, t_5, t_7\}$; $C_{12} = \{t_4, t_6, t_8\}$;

Finally, two activity chains, also two concurrent activity sequences, obtain, namely, $\sigma_{11} = \{t_3, t_5, t_7\}$ and $\sigma_{12} = \{t_4, t_6, t_8\}$. As previously shown, in the design of the multi-component coupling rotor system, the activity sequence consisting of the radial support components design t_3 , the radial components—rotor coupling structure design t_5 , and the radial components—rotor bearing capacity design t_7, and the activity sequence comprised of the axial bearing components performance design t_4, the axial components—rotor coupling structure design t_6, and the axial components—rotor bearing capacity design t_8, can be executed concurrently.

6.2 Design cycle

The analysis of the design cycle shown in Fig.8, results in three $T\_$ constants of the PN-PDDP through Eq. (5):
$J_1 = \{1,1,1,0,0,1,0,0\}$, $J_2 = \{1,1,1,0,0,0,1,1\}$,
$J_3 = \{1,0,0,1,1,1,0,0\}$. Accordingly, three design cycles obtain: $\sigma_1 = \{t_1, t_2, t_3, t_6, t_1\}$, $\sigma_2 = \{t_1, t_2, t_3, t_7, t_8, t_1\}$,
$\sigma_3 = \{t_1, t_4, t_5, t_6, t_1\}$.

6.3 Design conflicts

In the PN-PDDP of Fig.1, S_{D3} is the after set of the two design activities t_1 and t_{11}, which suggest that these two activities have conflicts at S_{D3}. This results in the conflict activity set $T = \{t_1, t_{11}\}$ and the conflict performance set $P = \{s_{P1}, s_{p2}, s_{p12}\}$. That is to say, in the design of the multi-component coupling rotor system, both the rotor structure design t_1 and the turbopump rotor system dynamics design t_{11} would operate on the shaft structure, leading to conflicts. The factors influencing the performance characteristics of the conflict include the rotor's positioning performance characteristics S_{p1}, the rotor's rotation performance characteristics S_{p2}, and the rotor system dynamics performance characteristics S_{p12}. Therefore, conflicts can be resolved through coordinating the demands of these three kinds of performance characteristics.

The solving program of the PN-PDDP characteristic parameters is developed by using VC++ interface, which achieves computer simulation of the design process model. The program's operation interface is shown in Fig.6.

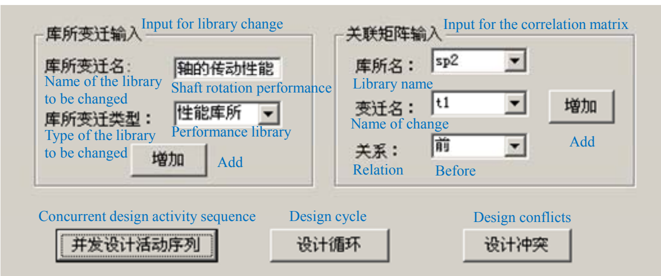

Fig.6. Interface of solving program for the PN-PDDP characteristic parameters

A case study of collaborative design has been conducted on the aforementioned multi-component coupling rotor system. Different design parties (alliances) could negotiate with the client about the multi-component design scheme via the real-time interactive system, and further decompose the design task into sub-tasks so as to be assigned to different entities. The component structure design entity uses the AUTOCAD secondary development program to conduct structure design, producing STL files, which are then sent to the processing technology analysis and design entity via e-mail. These two entities conduct relevant analysis, utilizing their respective resources, and then send the results back to the overall structure design entity via e-mail. The overall coupling structure design entity will save the drawings and parameters of different components in the product database when it completes its design. Using the data management services, the monitoring and control system design entity reads the structure data of varied components so as to monitor and control system design, and saves the results in the product design database. The dynamics analysis entity uses these data to conduct dynamics checking, sending the results back to the design alliance.

In this paper, a case design study was carried out. Fig.7 shows the special design drawing of the rotor shaft. Fig.8 indicates the modal graph resulting from the dynamics checking of the coupling system. Fig.9 demonstrates the interactive interface of the drawing of the multi-component coupling rotor collaborative design process.

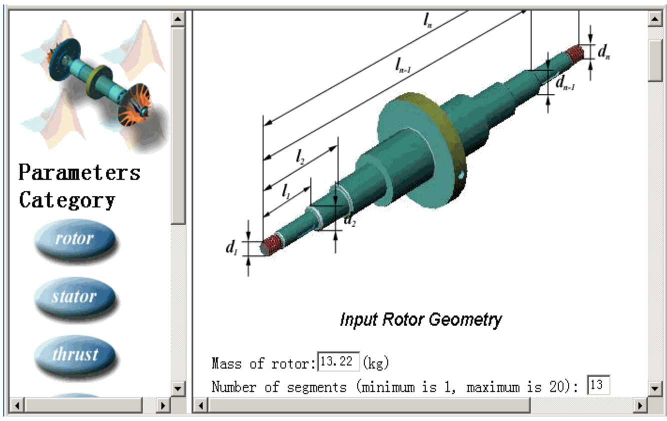

Fig.7. Rotor structure drawing

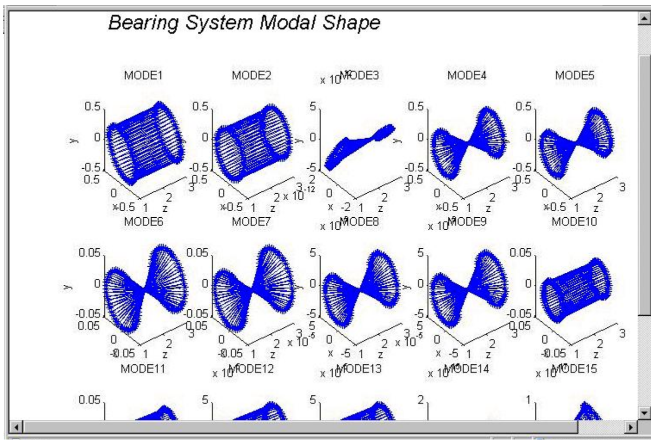

Fig.8. Dynamics checking results

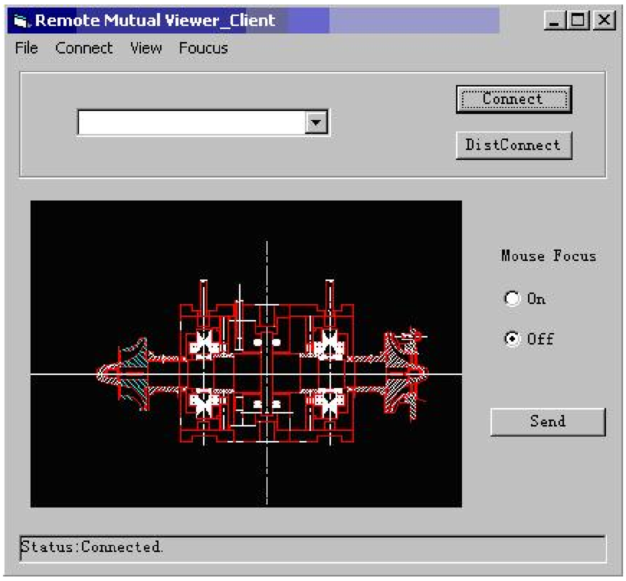

Fig.9. Interactive interface of the multi-component coupling rotor drawing

7. CONCLUSION

This paper presents a new design process PN-PDDP model and the study examined the characteristics of the PN-PDDP model coupling design process based on extended Petri nets, including concurrent activity sequence, reachability tree, design cycle, and design conflicts. Based on the definition of the design process spanning reachability tree, concurrent activity sequence, design cycle, and design conflicts, and determines their parameters, a solving method of those characteristic parameters is presented and successfully demonstrates the effectiveness of the model. This is illustrated through the solving program of the PN-PDDP performance characteristics.

The paper also presents the case study design process of a specific multi-component coupling high-speed turbopump. In the study, the relevant knowledge matrix is obtained and analysis software of coupling design is demonstrated to be able to handle the design activity support and conflict resolution . The design results are also discussed.

ACKNOWLEDGMENTS

This work was supported by National Natural Science Foundation of China under Grant [No.51575418], the Natural Science Foundation of Shaanxi Province of China under Grant [No. 2014JQ7252], and CSC (China Scholarship Council) scholarship.

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