The Complex Product Design Modeling Based on Spatial Sequence Colored Petri-nets

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Abstract—**Functional modeling is the mainly option in current conceptual design, which relies on the designers' subjective experience and lacks of intelligence. We choose behavior flow modeling which is more intelligent for conceptual design and express the behavior flow by establish the semantic network and Petri nets in this paper. At the end, we illustrate the expression of spatial sequence in behavior flow by the instance of auto engine design.**

Index Terms—**behavior flow, spatial sequence, semantic networks, Petri nets**

I. INTRODUCTION

Complex products mean the products, whose technology is intensive, the process management is complex, and the customer demand is ever-changed [1]. The stage of conceptual design is the core of the complex products design process, and the fundamental aspects to enhance the competitiveness of products [2]. The investigation data indicate that stage of conceptual design which only occupy 5% of the whole cost determine the 85% part of the cost in the product life-cycle, time and cost become the key factors as quality in the products design process. For the reason that conceptual design is at the earliest stages of the product life-cycle, it has great impact to the following stages [3]. The conceptual design fundamentally determines the features, quality, cost, developing time and the innovation, which includes the understanding of designers for design tasks, the expression of design inspiration and realization of designing concept.

Nowadays function modeling is the most common way of product modeling, which treat the function as the core of whole model through the study of product features, and build top-down functional decomposition model to guide functional modeling in general methods. The current establishment of functional decomposition method depends on the existing knowledge of functional division and the utilization and summary of the related experiences. These knowledge and experiences come from the staff of related fields which are unilateralism, and only can apply in some areas. Besides, the knowledge and experiences of the related staff which are valuation function to find functions design optimization solution through partial validation, is not guaranteed to be the best solution. At the last, if the design results of proposed model do not have the possibility, everything is meaningless. So the function modeling is a process which is from subjective to objective, and from abstract to specific, the former top-down methods will cause the mismatch of results and reality [4].

Based on above reasons Gero proposed FBS (Function-Behavior-Structure) model in product design, he believes that product design is a process which converts the functional requirements of designers into the behavior that expected to achieve the function, and then select the appropriate structural elements based on the behavior, finally, make comparison between the actual behavior of the selected structural element and the behavior which is expected to achieve the function, if the result match the expectation, the structural element is what we need, if not repeat the former process[5]. After the proposed FBS theory, designers focus on the research of the behavior in the product conceptual design, and resolve the problems we mentioned before through building the behavior flow of products. The behavior is objective, and can express the modeling process of complex product without ambiguity [6]. On the other hand, we can clearly define the series of states in the modeling process by research the behavior directly, especially for the initial state and the target state. Thronging the two states and behavior triggered by the state-changed, we can get the optimal behavioral sequence to achieve the changing of states to realize innovation in product design and build the new behavior flow model of new product. In addition, behavior can be directly mapped to structure; the behavior flow model is practical and covers the entire life cycle of intelligent design.

Although the behavior flow modeling has been proposed [7], we do not have deep analysis about this concept, so this paper will make further research for the expression of behavior flow. In this paper we express the product intelligent design in the aspect of evolution of

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spatial sequence by proposing the brand-new concept about spatial sequence of behavior flow. The subsequent chapters of this paper will propose two types of expression of spatial sequence of behavior flow, and the conversion principles between these two types.

II. Framework of Spatial Sequence Modeling in Behavior Flow

It's necessary to give the definition of behavior before proposed the concept of spatial sequence:

Definition1 Behavior: In FBS model, behavior is the changing process between the states of structure, after the change happened, the feature will be realized by related structure.

On the basis of the definition of behavior we can know that some certain function can be achieved after the changing process of the structural state, and the product features cannot be done by a single function, but requires a series of sub-functions to be achieved in specific order, so there will be flow of a series of behavior. The behavior is the element of the flow. Now the concept of behavior flow comes up.

Definition2 Behavior flow: A series of structural states changed in specific temporal and spatial order, resulting in a series of sub-functions to be achieved, and finally complete the main function.

There will be a spatial changing sequence in the changing process of structure, we can resolve the interference problems and realize structural optimization by researching the spatial sequence in the initial phase of conceptual design.

Definition3 Spatial sequence of behavior flow: To achieve a specified function, the spatial relationship between joined structures will produce a series of state-changing which can be passed by the driven of behavior, the passing path of spatial relationship between joined structures is the spatial sequence of behavior flow what we mentioned above.

From the definition of spatial sequence we can see that behavior is the driver of the state-changing of spatial structure. The passing path should be constrained by spatial joined factor, which is the parameter constraint such as angle, distance and frequency, involved in spatial relationship of joined structures. Now we can get the mathematical definition of the node of spatial sequence:

$$\mathbf{B}(\boldsymbol{S_1}, \boldsymbol{S_2} \dots \boldsymbol{S_n}; \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma} \dots) \quad (2.1)$$

B means the behavior which drives the state-changing of spatial sequence, $S_1, S_2 \dots S_n$ means the structural elements of the product, α, β, γ ...meansspatial joined factor which constrains the passing path. We can get the mathematical definition of spatial sequence which consists of a series of nodes:

$$\boldsymbol{\pi} = \boldsymbol{B_1} \boldsymbol{B_2} \boldsymbol{B_3} \dots \boldsymbol{B_k}(\boldsymbol{S_1}, \boldsymbol{S_2} \dots \boldsymbol{S_n}; \boldsymbol{\alpha}, \boldsymbol{\beta}, \boldsymbol{\gamma} \dots) \quad (2.2)$$

Form the definitions we can see that the spatial sequence can produce the state-changing driven by behavior and constrained by spatial joined factor, and will finally realize specified function.

Now we can get the modeling framework of spatial sequence in behavior flow, as shown in Figure 1.

III. Predicates Matrix of The Relationship Between Spatial Joining In Behavior Flow

Before we propose the conception of predicates matrix of the relationship between spatial joining in behavior flow, it's necessary to introduce the semantic network as theoretical basis. The spatial sequence in behavior flow is essentially the changing series of joining relationship between structures in the product modeling process, and the semantic network can express well the relationship between concepts through the conceptual nodes and connection arcs, so we use semantic network to describe the joining relationship between the structures in this paper [8]. In the semantic network of spatial sequence, the connection word is the joining relationship between structures, and the noun is the structure, so the BNF paradigm is as following:

<Spatial sequence>:: = <structural unit><joining relationship><structural unit>
<Structural units>:: = <noun N> | <group of nouns>
<Join relation>:: = <connection word L> | <group of connection words>

The structural units in product is organized by specified joining relationship, and form the spatial joining relationship of structural units, so we can call this relationship network as semantic network of spatial sequence. Valve works as an integral part of engine, its behavior flow has a typical passing path in the spatial sequence, so we will use valve as an instance to illustrate the expression of spatial sequence in behavior flow.

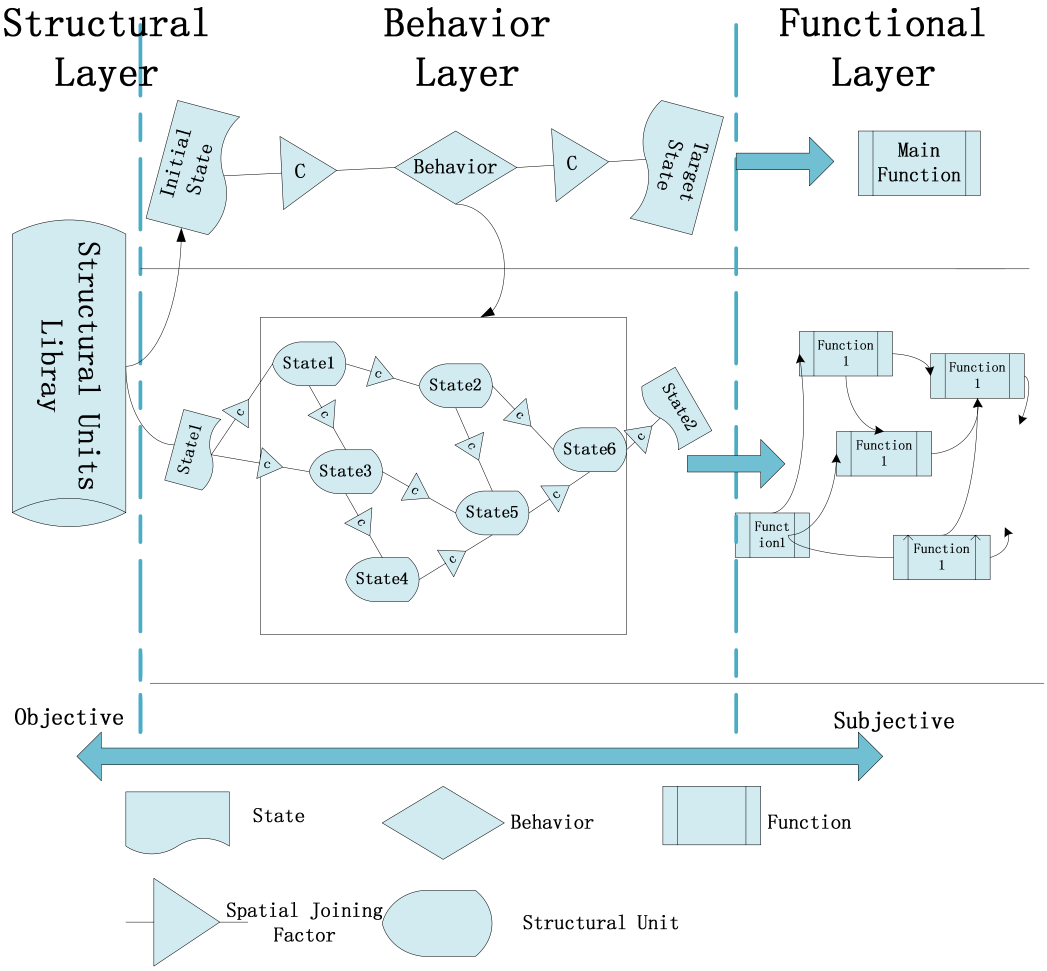


Figure 1. Modeling framework of spatial sequence in behavior flow

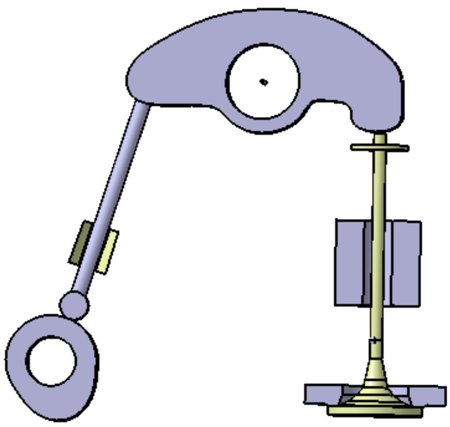
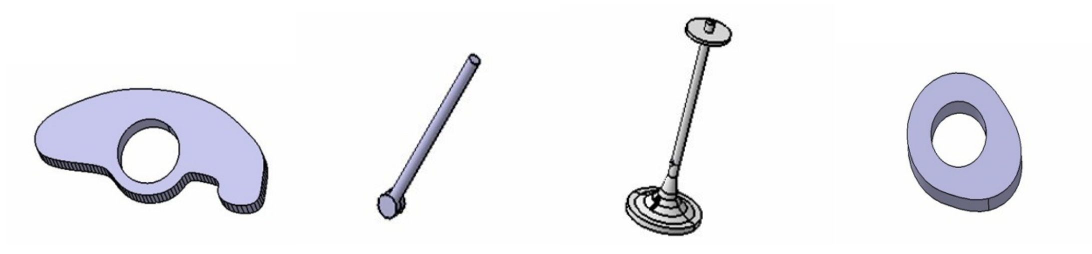


Figure 2. Assembly of engine's valve

We will encode the structures and the joining relationship between them which are involved in the valve to construct the semantic network of spatial sequence as shown in figure3.



Rocker Rod Valve Cam

Figure 3. The spatial sequence

TABLE I

CODING OF THE VALVE'S STRUCTURES

Name	Rocker	Rod	Value	Cam	Ground	Spring
coding	P01	P02	P03	P04	P05	P06

TABLE II

CODING OF SPATIAL JOINING RELATIONSHIP

Spatial joining relationship	Combine		Contact			Angle
	Concentric	Coaxial	Point Contacted	Line Contacted	Surface Contacted	
coding	R01	R02	R11	R12	R13	R2

Now we can construct the semantic network of spatial sequence in valve's behavior flow based on the coding, which is shown below in figure 4:

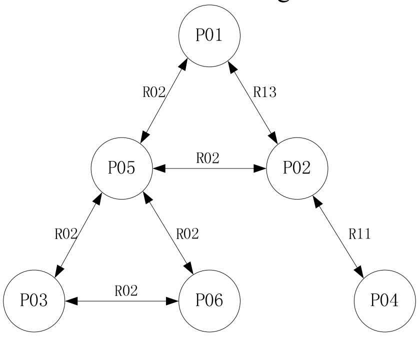


Figure 4. Semantic network of spatial sequence

Based on the construction of semantic network, we can now build the Space Join Relationships Predication Matrix (SJRPM) to express the joining relationship between the structural units, which the meaning of the rows and columns are the coding of the valve's structures as mentioned in table1, and the data is the matrix is the coding of spatial joining relationship. The mathematic definition is:

$$\mathrm{D} = \det(a_{ij}) = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$$

(1) $\mathrm{i}, \mathrm{j} \in$ {coding of the valve's structures},

(2)$\exists\ \mathrm{R}(P_i, P_j) \neq 0 \Rightarrow a_{ij} = r_{ij} \in$ {coding of spatial joining relationship}

After we define the conception of SJRPM, we can convert the semantic network to the corresponding SJRPM D:

$$D = \begin{vmatrix} 0 & 13 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ 0 & 0 & 0 & 13 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

IV. MODELING OF SPATIAL SEQUENCE COLORED PETRI NETS

4.1 Spatial Sequence Colored Petri Nets

Colored Petri-net works as an extended form of Petri-net, which can effectively help user to deal with the expression of knowledge that contain massive detail information and are high related [9]. In this paper we propose Spatial Sequence Colored Petri-Net (SSCPN) on the base of colored Petri-net to describe and analyze the spatial changing path of structural units to achieve some specified functions in the product modeling process.

Definition4 Spatial sequence colored Petri nets:

SSCPN=$(\sum\ , \mathrm{P}, \mathrm{T}, \mathrm{R}, \mathrm{N}, \mathrm{O}, \mathrm{G}, \mathrm{F}, \mathrm{I})$,

(1)Σ: set of colors, used to describe the structural unit involved in the spatial relationships.

(2) P: finite set of places, used to describe the spatial joining relationship between the structural units.

(3) T: finite set of transactions, used to describe the behavior which drives the passing of special sequence.

(4) R: the set of directed arcs, P ∩ T = P ∩ R = T ∩ R = ∅, used to describe the spatial joined factors.

(5) F: finite set of conditional functions; the directed arc means that the system status only changes when the transaction happens.

(6) I: initialization function.

4.2 Spatial Sequence Colored Petri Nets in Design of Auto Engine's Valve

The valve of the engine is the device which is in charge of intake the fuel and exhausts the burned gas, and the spatial joining relationships between all the structural units change constantly by the driver of behavior, the coaxial relationship between cam and the engine ground convert to the coaxial relationship between connecting rod by the driver of rotational behavior, and the spatial joining relationships keep passing in the same pattern until there is a coaxial relationship between valve and the engine ground[10]. The whole process can be described by SSCPN, which is shown in Figure 5.

The exact signification of the places and transactions in this figure showed as below in table III:

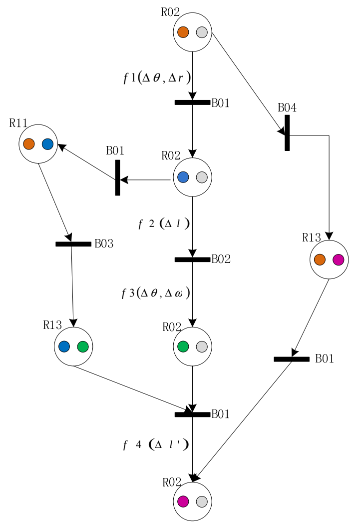


Figure 5. The SSCPN of spatial sequence in the process of valve moving

TABLE III
THE SIGNIFICATIONS OF PLACES AND TRANSACTIONS

Components of Petri-nets	coding	Exact signification
Places	P1	The coaxial relationship between cam and engine ground
	P2	The point contacted relationship between cam and connecting rod
	P3	The coaxial relationship between connecting rod and engine ground
	P4	The surface contacted relationship between connecting rod and rocker
	P5	The coaxial relationship between rocker and engine ground
	P6	The surface contacted relationship between valve and rocker
	P7	The coaxial relationship between valve and engine ground
Transactions	B1	The rotational movement of cam and engine ground
	B2	The reciprocated movement of connecting rod and engine ground
	B3	The shimmied movement of rocker and engine ground

4.3 THE SPACE JOIN RELATIONSHIPS PREDICATION MATRIX OF THE SPATIAL SEQUENCE IN THE VALVE DESIGN

This process can also be described by SJRPM which mentioned in the chapter3, the SJRPM and SSCPN can be converted to each other, and the passing factor of the matrixes evolution are the behavior and the parameters involved in the movement. So the SJRPM of the spatial sequence in the valve can showed as below:

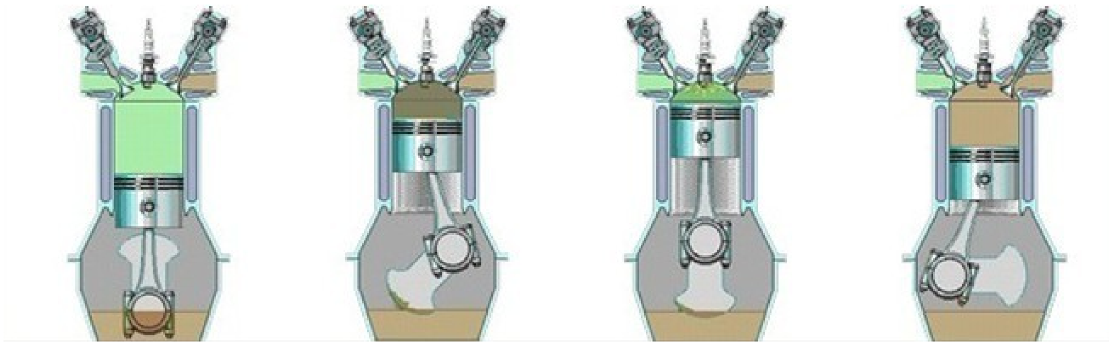
$$\begin{vmatrix} 0 & 13 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ 0 & 0 & 0 & 13 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \xrightarrow{B_{01}(S_4,S_5;\Delta\theta,\Delta r)} \begin{vmatrix} 0 & 13 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 11 & 2 & 0 \\ 0 & 0 & 0 & 13 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix} \cdots\cdots\cdots\cdots\cdots \xrightarrow{B_{02}(S_2,S_5;\Delta\theta,\Delta\omega)} \begin{vmatrix} 0 & 13 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ 0 & 0 & 0 & 13 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

$$\xrightarrow{B_{03}(S_3,S_5;\Delta l)} \begin{vmatrix} 0 & 13 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 11 & 0 & 0 \\ 0 & 0 & 0 & 13 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}$$

V. THE INSTANCE OF EXPRESSING ENGINE BASE ON SPATIAL SEQUENCE OF BEHAVIOR FLOW IN THE COMPLEX PRODUCTS MODELING

In order to express the behavior flow involved in the process of product design through the spatial sequence, we take engine as instance to analyze this issue. The engine is an energy conversion mechanism; it can convert the heat energy created by burning the fuel to mechanical energy. To achieve this conversion, we

to the end line, then the gas burns and expands to push the piston move downward for the realization of power creation, finally exhaust the gas which have been burned. Now we can conclude four processes which are intake, compression, powering and aerofluxus by what should lead the combustible mixed gas into the cylinder firstly, compress the gas and light it when it come close we mentioned before. These four processes named a work cycle of the engine, the cycle repeated constantly to realize the conversion of energy and make the engine working continuously.



Intake Compression Powering Aerofluxus

Figure 6. Operational principle of four cylinder engine

In the process of intake, the crank rotates, and the piston moves from TDC to the BDC, at this moment the exhaust valve closed and the intake valve open. At the beginning of intake process, the piston located at the TDC, there is some unexhausted gas in the cylinder, so the air pressure inside the cylinder is a little higher then atmospheric pressure. As the piston moves down, the volume of the cylinder increases, and the air pressure decreases, when the air pressure is lower than the atmospheric pressure, the vacuum attractive force generates in the cylinder, the air and the gasoline mixes into combustible mixed gas, and is attracted into cylinder until the piston moves down to the BDC.

During the gas compression, the crank keeps rotating, and the piston moves from the TDC to the BDC. At this moment, the exhaust valve and the intake valve are both closed, so the cylinder becomes a closed volume, the mixed gas has been compressed, the pressure and the temperature keep rising, and the process ends when the piston moved to the TDC.

The intake valve and the exhaust valve both keep closed in the powering process, when the piston move near to the TDC, the spark plug generates spark and light the mixed gas, the gas burned and release lots of heat which make the gas temperature and the pressure increase, the gas expands and push the piston moves from the TDC to BDC, makes the crank rotates to output the mechanical power through the connected rod [11]. As the piston moves down, the volume inside the cylinder increases, the pressure and the temperature decrease, the process ends when the piston moves to the BDC.

The exhaust gas generated after the mixed gas burned must be discharged from the cylinder to continue the next cycle. At the end of powering, the exhaust valve open but the intake valve is still closed, the exhaust gas can be discharged by its own pressure. When the piston moves beyond the TDC, the exhaust valve closed, and the exhaust process ends.

The four spatial sequences in behavior flow which are involved in the four processes can be expressed by SSCPN, as shown in figure 6:

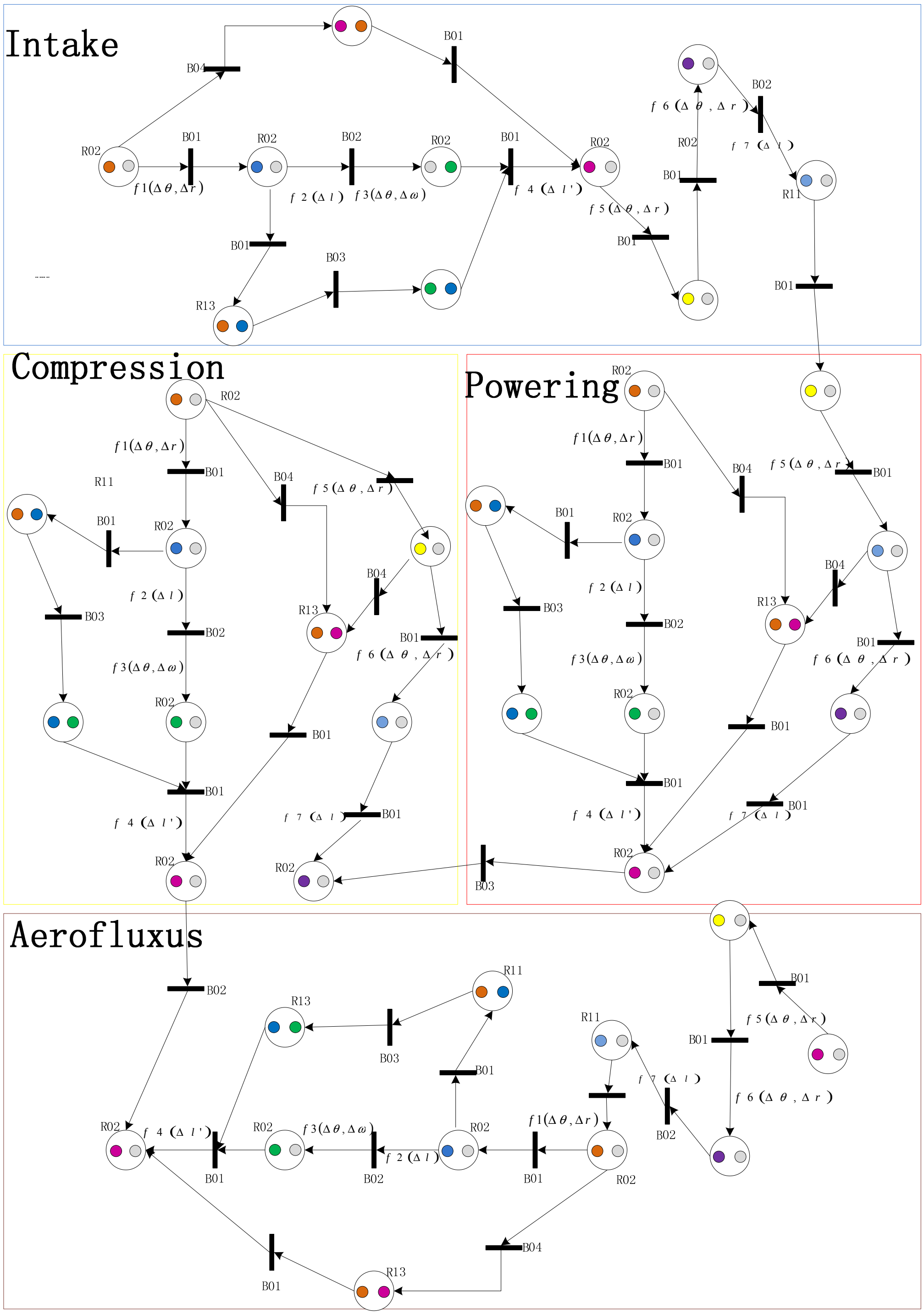
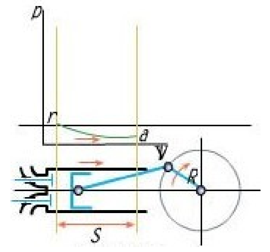
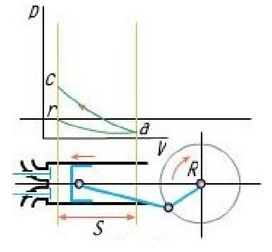
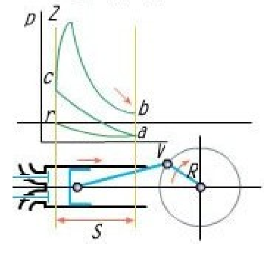
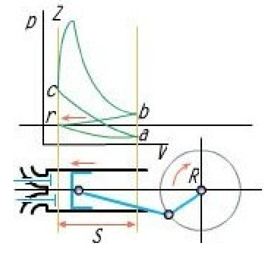
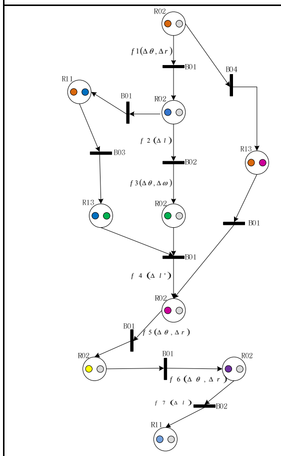
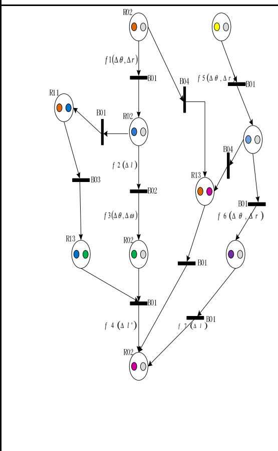
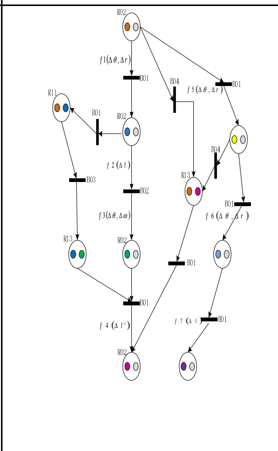
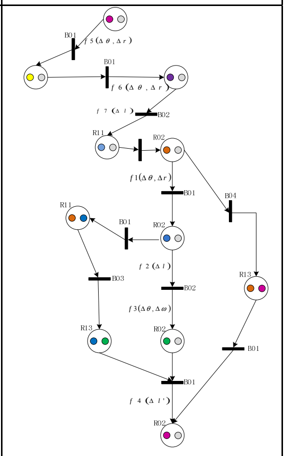


Figure 7. The SSCPN expression of four processes

The detail analysis shown as in table IV:

TABLE IV
DETAIL ANALYSIS OF FOUR PROCESSES

Intake	Compression	Powering	Aerofluxus
			
			
$\begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&0&0\\0&0&0&13&0&0\\0&0&0&0&2&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix} \xrightarrow{B_{01}(S_4,S_5;\Delta\theta,\Delta r)} \begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&2&0\\0&0&0&13&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix}$	$\begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&0&0\\0&0&0&13&0&0\\0&0&0&0&2&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix} \xrightarrow{B_{01}(S_4,S_5;\Delta\theta,\Delta r)} \begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&2&0\\0&0&0&13&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix}$	$\begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&0&0\\0&0&0&13&0&0\\0&0&0&0&2&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix} \xrightarrow{B_{01}(S_4,S_5;\Delta\theta,\Delta r)} \begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&2&0\\0&0&0&13&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix}$	$\begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&0&0\\0&0&0&13&0&0\\0&0&0&0&2&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix} \xrightarrow{B_{01}(S_4,S_5;\Delta\theta,\Delta r)} \begin{vmatrix}0&13&0&0&0&0\\0&0&0&11&2&0\\0&0&0&13&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\\0&0&0&0&0&0\end{vmatrix}$

VI. CONCLUSION

In this paper we propose two kinds of expression models of spatial sequence in behavior flow based on the current research, which are predicates matrix of the relationship between spatial joining in behavior flow and spatial sequence colored Petri-net. They all solve the express issue of behavior from two different aspects, which also can be converted to the other, and they express the transfer process of spatial sequence in behavior flow in the process of complex product modeling exactly. In additional they provide the basis of theoretical expression for the research of the application of behavior flow in complex product modeling.

The product modeling based on behavior flow is an extremely complicated and creatively process, there are much work to be done to realize the automated and intelligent design based on the current technical level. So we need research not only the field of design and computer modeling, but also the field of cognitive science, notice science and system science. The only way to achieve the new level of intelligent design is innovate design theory and express function constantly.

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