

## Product Spatial Sequence Modeling based on Spatial State Transition Petri Net of Behavior Flow

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### Abstract

*FBS model proposed three levels of abstraction (function, behavior, structure) and eight design stages used to describe the design. The model becomes the basis of many computer-aided design practices. In this paper, based on FBS model, behavior flow ontology conception is proposed, and the conception can describe the dynamic and continuous of behavior of products more accurately. The behavior flow mechanism extends to structure layer too. Spatial sequence is the exhibition of behavior flow in the structure layer. This paper analyzes the relationship between behavior flow and spatial sequence, and the relationship between spatial sequence and function. A model to express the spatial sequence of behavior flow is proposed, by dividing spatial sequence into two parts, spatial connection relation of product and spatial state transition process. Spatial connection relation is the description of the product composition, expressed by spatial semantic network; the spatial state transition process of behavior flow is the process to realize the function, expressed by spatial state transition Petri net of behavior flow. Spatial sequence of behavior flow of engine is represented by this model as an example. Finally, a conceptual design framework based on behavior flow is proposed as the further research direction.*

**Keywords:** FBS model, behavior flow, spatial sequence, state transition petri net, conceptual design

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### 1. Introduction

The product development process is the transfer process from customer requirements to a physical structure. During the transfer process, the conceptual design is the most important stage. Studies have shown that the conceptual design phase commits 70%-80% of cost of product development life-cycle, and determines the innovative level of final product [1]. As the earliest stages of product life-cycle, conceptual design has a tremendous impact on follow-up design stages. The conceptual design stage not only largely determines the product's features, quality, cost and development time, but also determines the product innovation level. Conceptual design includes the designer's understanding of the design task, the expression of design inspiration, and the play of design idea.

In the conceptual design stage, designers produced physical configuration to meet function specification. In previous studies, function - structure mapping can be attributed to two main categories: direct mapping and indirect mapping. Catalog drive function-structure mapping [2] is a direct mapping. Function-behavior-Structure (FBS) model is the typical indirect mapping methodology. Gero proposed FBS model as a means of understanding product design and the basis of develop computer-aided design computer tools.

According to FBS model, the function layer is firstly mapped to behavior layer, and then the behavior layer maps to structure layer. However, the FBS model does not involve the mapping rules between the three layers.

In the FBS model, the proposed behavior makes the mapping from function to structure more natural and objective. Many of the current study of conceptual design are based on this model. Christophe Fet al integrate knowledge model into the FBS model, and get a conceptual design model, which can be implemented easily by computer application [3]. Chen and Pan proposed a state space exploration based creative design model based on the FBS model [4], that model conducts analogy-based design based on similarity of the structure, behavior, or functions, and introduces the new structure, behavior or function from the source design into the target design. The situated FBS model adds the context model, and reconstructs the eight fundamental design process of FBS model, so that the model meets the dynamics of the design

context more accurately [5]. Wan et al consider the multi-functional properties of the basic structure and express each function in FBS model with basic operating actions and set up model of function decomposition and structure matching with the aid of quotient space theory, used to re-innovative design [6]. Among many studies based on FBS model, almost few have developed systematic definition and model for behavior, the key variable in FBS model.

The conception of behavior flow was proposed in engine modeling research recently and defined as the state change process of matter during the behavior process [7]. Behavior flow can express the continuity and dynamics of the process, that behavior realizes the function and it's the super set of behavior. In this paper, the new systematic ontology definition of behavior flow is given, and the behavior flow mechanism is integrated into the whole process of the FBS model. Spatial sequence is the realization of behavior flow in the structure layer. A model is proposed to express the spatial sequence mechanism and the spatial sequence model of engine product is constructed with this model as an example in this paper. Finally, a conceptual design framework is proposed as the follow research direction.

## 2. FBS Model and Behavior Representation

FBS model and the behavior is the basis of this study. This section introduce FBS model briefly and describes the methods to represent behavior.

### 2.1. FBS Model

FBS model is based on three variables describe different aspects of the design object: function (F) variable describe the purpose of design object, behavior (B) variable describe properties generated by the structure of design object, structure (S) variable describes design object's components and their relationships. Designers build associations between function and behavior, behavior and structure, and firstly map function to behavior, then map behavior to structure. Therefore, the designer does not construct direct relationship between function and structure with FBS model. According to FBS model, function, behavior and structure is defined, as shown in Table 1.

Table 1. The Definition of Function, Behavior and Structure

Function	The abstract description of design object (independent from implementation)
Behavior	A series of state changes of physical structure in certain period time
Structure	Product material, geometry and topology

FBS model represents design by a collection of the design processes, which link function, behavior and structure together [2]. These processes can be seen as different stages of the design. As Shown in Figure 1, the eight processes FBS model described is outlined briefly as follows:

**Formulation (process 1):** The design requirement described by the function (F) is transformed into the behavior (Be) that is expected to be able to achieve function.

**Synthesis (process 2):** The behavior (Be) is transformed into structure (S) that is expected to exhibit the desired behavior (Be).

**Analysis (process 3):** The actual behavior (Bs) is derived from the resulting structure (S).

**Evaluation (process 4):** The actual behavior (Bs) and the expected behavior (Be) are compared to determine whether the design is to be accepted.

**Documentation (process 5):** Record design description (D) for the manufacture of the product.

**Reformulation (the process 6, 7 and 8):** When the actual behavior does not meet the requirements, processes 6, 7 and 8 address changes in the design state space in terms of structure, behavior and function variables respectively.

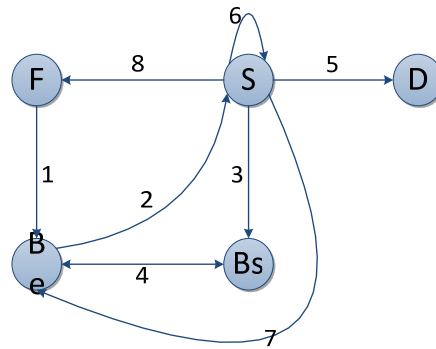


Figure 1. FBS Process Model

## 2.2. Behavior Representation

In the FBS model, the behavior is the properties generated by structure. As a bridge between function and structure in FBS model, the behavior plays a vital role in it. There is a dominant view for the behavior: it relates to state changes of physical structure, it changes temporally, thus causing the state transition, or it remains unchanged to satisfy specific function. How to represent a behavior is an important aspect in conceptual design of FBS model. There exist mainly two ways to represent the behavior currently: input and output flow of object (object refers to the energy, material and signal) and the state transition methods [8].

Input and output flows represent a behavior with the input and output of that behavior. For example, the behavior "to magnify force" (B1) of lever can be expressed as the input and output pull/push force. This method just expresses a particular aspect of behavior that is the effect of behavior and cannot express the behavior itself, the "flow". There are many attributes of a behavior, and the attributes of B1 might contain: the strength of the input force and output amplified force; the distance between the two endpoints and the pivot of the lever; the direction and distance for movement of the respective ends. Which can be seen, input and output flow can only express only one aspect of behavior, which is the major drawback of this representation?

State transition way sees behavior as the transition chain or network of physical states. It is believed that the state transition view is the only general view of behavior in this paper and it reflects some kind of "flow" of the behavior. For the behavior opening the door (B2), two states can be defined, which are "on" and "off", then the behavior can represent by the transition process from state "on" to state "off". However, this expression also has its drawback, it can only express the state change process of the overall structure of the product, and the relations and mechanism of states transition between components and between components and environment is out of its range.

For behavior of mechanical design, there is a more useful view at conceptual design stage: behavior is physical interactions between the product components and between product components and the environment. The state of the product changes when a behavior is executing, while a series of interactions happen in the internal of product and between the product and the environment, and these interactions cause the physical state transition from the product components to other component or environment objects. U. Roy modeled the part behavior in the interaction view, and proposed that the part function is completed by the interaction among parts of the product under a series of assembly constraints [9].

## 3. Behavior Flow and Spatial Sequence

### 3.1. The Definition of Behavior Flow

Behavior is the state's transition of product physical structure over a certain time. Both input and output flow and state transition method try to express behavior with the idea "flow", but are limited to behavior level, and limited to a particular behavior object. This behavior is viewed from a functional perspective in this paper, and the function achieved through the execution of

behavior, which converts certain input to specific output. Complicated behavior can be further divided into lower-level behaviors.

**Definition 1:** behavior (B) is the transition from one state to another state of physical structure. If a behavior cannot be divided into lower-level behaviors, then it is called meta-behavioral, expressed with the formula  $O = \gamma(I)$ , where I is the input set of the behavior, O is the output set of the behavior. If the input and output are not concerned, it can be abbreviated by  $\gamma$ . respectively, if a behavior contains a number of lower-level behaviors, it is called complicated behavior.

The input and output of behavior is the same as input and output of function that is implemented by that behavior, which can be energy, materials or signals. Some behaviors have no input or output, such as the support behavior of a foothold. Some functions are achieved by concurrent behaviors ( $F \leftarrow B_1 \cup B_2$ ), while some are achieved by the serial behaviors ( $F \leftarrow B_1 B_2$ ) [6]. Any product functions are achieved through a sequence of behaviors that is the connection of behaviors in series and parallel relations. Complicated behavior itself can be generated by lower-level behaviors with series operation and parallel operation.

**Definition 2:** behavior flow is a sequence of behaviors that can realize certain function that can be recursively expressed as follow formulas:

$$\begin{cases} BF \rightarrow B & (1) \\ BF \rightarrow (BF + BF) \mid (BF \cup BF) & (2) \\ BF \xrightarrow{\text{implement}} F & (3) \end{cases}$$

BF represents behavior flow; B is a behavior, the symbol "+" indicates series operation, and the symbol "U" indicates parallel operation. The items separated by the symbol "|" have the "or" relation, F is the function implemented by BF. Equation (1) implies that a single behavior is a behavior flow, even the meta-behaviors, which are simplest behavior flows. Equation (2) says that a more complicated behavior flow can be generated by two other behavior flows with the series operation or the parallel operation. Equation (3) expresses a necessary requirement of a behavior flow that it must realize certain function. If the behaviors are just combined messily together and can't realize respective function, then it cannot be called a behavior flow.

Behavior flow is a sequence of behaviors, and a meta-behavior can be regarded as the simplest behavior flow. The behavior flow is the mean to achieve function, while function is the explanation and object of flow behavior. There are hierarchy relations in behaviors. As the same reason, there is hierarchy relations in behavior flows, such as behavioral flows ( $B_1(B_2 \cup B_3)$ ) can be decomposed into ( $\gamma_1 \gamma_2 \gamma_3(B_2 \cup B_3)$ ), where  $B_1 = \gamma_1 \gamma_2 \gamma_3$ , and that behavior flow can be further broken down, until every element of that behavior flow is a meta-behavior.

### 3.2. Spatial Sequence Model

On the behavior layer, behavior flow sees a sequence of behaviors. Because behavior is state changes of physical structures, the behavior flow is essentially the sequence of physical states in changing. At the process of implementation of product functions, a lot of interactions happen, between components, between component and environment, the environment refers to other objects except the product structure itself, such as materials, air and etc. Spatial sequence is behavior flow on the structure layer. In the spatial sequence model, the environmental objects will also be considered.

**Definition 3:** At the process of the implementation of product function, the product structure and the environment objects, which interact with the product structure, are called the product space. Define the physical structure of the product as a real space S, environment objects as a virtual space V. Product space can be expressed as:

$$PS = (S; V) \quad (4)$$

**Definition 4:** product spatial sequence is defined as the states transition sequence of product space during the implementation of product function. Spatial sequence model can be expressed a continuous mathematical function curves, the value of any point of the curve depends on the following two variables: state of the structure (s), state of the environment (v). The product spatial sequence model can be described as follows:

$$\begin{cases} PS = f(s, v) \\ s = S(t) \\ v = V(t) \end{cases} \quad (5)$$

Where  $s$  is state variables of the structure,  $v$  is the state variable of the environment,  $t$  is continuous time closed interval  $[t_1, t_2]$ ,  $t_1 < t_2$ ,  $t_1$  start time for the function realization,  $t_2$  for the end time;  $PS(t_0), t_1 \leq t_0 \leq t_2$ , indicates the product space state at the time  $t_0$ . As shown in Figure 2, spatial sequence is the state changing sequence of product space at certain time interval.

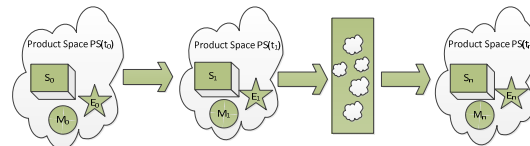


Figure 2. Spatial Sequence Model

Spatial sequence is the performance of behavior flow in structure layer, so from the perspective of product spatial sequence model, behavior flow is the state sequence of product space. It can be expressed as follow formula:

$$BF = (PS_0, PS_1, \dots, PS_k) \quad (6)$$

Where  $PS_i$  is a product spatial state at a particular time?

Product spatial state changes through the interactions between components of product structure, between components and environment objects. The mechanism of state transition is that the state changes of some components trigger the changement of states of other components or environments objects.

### 3.3. Function, Behavior Flow and Spatial Sequence

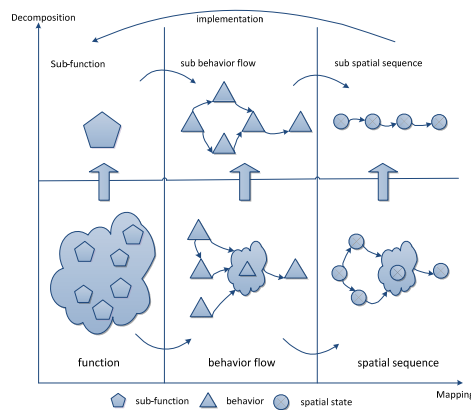


Figure 3. The Relation between Function, Behavior and Spatial Sequence

Figure 3 describes the mapping relations among function, behavior flow and spatial sequence. Function is a description of the purpose of product design. Function is the result of certain behaviors or actions, and is the abstraction of behaviors or actions. For complicated function, it can be further portioned into several sub-functions, and then sub-functions can

continue to decompose until all sub-functions are meta-functions. There is a problem of decomposition granularity, for when to stop decomposition, there is no clear standard [10].

For each function, whether complex or simple, there is one to one mapping with a behavior flow. Behavior flow is the specific execution sequence of behaviors set, appears as the product space on structure layer, which is the process of changement of product space states. Any function or meta-function can be achieved by a behavior flow, and behavior flow is the process of function realization, while function is the result of behavior flow. A function can be expressed by the initial state  $PS_0$  and final state  $PS_T$  of behavior flow together. If a function  $F$  is composed by several sub-functions  $\sum_1^n F_i$ , then that function can expressed by a state matrix of product space states:

$$F = \sum_1^n F_i = [PS_{i0}, PS_{iT}]_n \quad (7)$$

Where  $PS_{i0}$  is the initial spatial state,  $PS_{iT}$  is the final spatial state,  $[PS_{i0}, PS_{iT}]$  represents sub-function  $F_i$ .

The realization of function ( $F$ ) is the transition process from input to output, input can be energy, materials and/or signal, the output is the target state of function. Functions can be divided into sub-functions according to logic relations, and there are serial and parallel relations between these sub-functions. Function is the description of design target, and the behavior flow is underlying causes of function realization, while the spatial sequence is the external appearance on structure layer. Structure of mechanical product is a set of geometry components and the relations between components, which is the carrier of behavior flow. Behavior flow acts under the constraints of the physical rules, and produce spatial sequence. The final state of spatial sequence means the implementation of a function.

#### 4. The Model to Represent Spatial Sequence

Spatial sequence is the performance of behavior flow in the structure layer, and seems as the state change sequence of product space. For the spatial sequence, there exist two different views to express it: global view takes the entire product space as a whole, and the spatial sequence described as a sequence of state changes of the entire product space; local view describes the state of product components and environment objects separately, spatial sequence is expressed as a sequence, which is the process that the state changes of some design objects lead to state changes of some other objects, then to another some objects, until the fulfillment of the function. The model combines the two views, and splits the representation of spatial sequence into two parts, the overall composition of product space and the state transition process among design objects, which are represented by spatial semantic net and spatial state transition Petri net respectively.

##### 4.1. Spatial Semantic Net of Behavior Flow

Behavior flow relates to the state changes of physical structure. The physical state changes causing the transition of the state changes or remain the same to complete specific function. Behavior flow is the sequence of behaviors to complete specific functions, and it is essentially the state transition process between design objects, so from the perspective of product space model, behavior flow is the interaction mechanism between design objects, and that mechanism explains the state change relations between design objects. The design object contains components objects of physical structure and environment objects.

Spatial state transition happens through the interaction between design objects, so the connection relationships between design objects are the key to the transition of the states. Behavior semantic representation model established by defining the behavior semantic vocabularies and set up primitives of function to express function [11]. Similarly, a connection semantic vocabulary is built for the semantic net [12] to represent the constitution of product space. Spatial semantic net of behavior flow is constructed based on the connection semantic vocabularies.

**Definition 5:** Connection semantics vocabulary: words used to define the connection type between two design objects, which determine the interaction between two objects. Some of semantic vocabulary is defined as follow:

Spin connection (R1): one of the two connected objects can rotate around the axis of the other one.

Translation connection (R2): one of the two connected objects can move on a surface of the other one.

Plane connection (R3): two connected design objects contact on the plane.

Fixed connection (R4): two connected fixed design objects link together, there is no relative motion between each other.

Point/plane connection (R5): a point of one design object contact with a plane of the other design objects.

Cylinder connection (R6): the cylinder faces of two cylindrical objects fit.

Rolling curve connection (R7): a hemispherical or spherical object N1 connects with a hollow hemispherical object, and N1 can roll on the spherical face of N2.

Gear connection (R8): two objects connect on gear or rack faces.

Screw connection (R9): the connection between the two objects is similar to the screw/nut connection.

Loose connection (R10): two objects contact with each other at some time, and are separated from each other at other time.

Connection semantics words are not limited to the 10 above, and can be freely defined according to different design domains.

**Definition 6:** Spatial Semantic net is the constitution of product space with the connection semantic words. The follow is the BNF paradigm of spatial semantic net of behavior flow:

```

<Spatial structure>:: = <joint unit> | <spatial structure><joint unit>
<Spatial structure>:: = <design object>
<joint unit>:: = <design object><connection semantics><design object>
<connection semantics>:: = <connectionword V> | <connectionwords>
<design Object>:: = <term N>
  
```

Spatial semantic words generally express the interaction of design objects of product space of mechanical products. Joint unit expresses a specific connection relation between two design objects. Except the one-object products, the constitution of product space can be expressed with a collection of joint units. Connection semantic words indicate the connection type, and there can be more than one connection relations between two objects. Figure 4 shows the spatial semantic net of behavior flow of engine intake components.

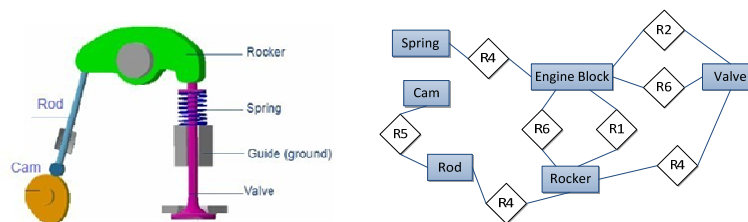


Figure 4. Spatial Semantic Net of Behavior Flow of Engine Intake Components

#### 4.2. Spatial State Transition Petri Net of Behavior Flow

Petri net is a mathematical tool to describe discrete and parallel systems, and suit for represent asynchronous, concurrent model. Zhaoli Zhang and etc. represent the model of knowledge flow [13] with this tool. Similarly, behavior flow model is represented by the Petri net. In the Petri net model of spatial state transition process of behavior flow, the libraries are used to represent the state of product space; transition nodes describe the transition of states. The transition direction of spatial state of behavior flow is expressed by the direction of the arc.

**Definition 7:** Spatial state transition Petri net of behavior flow  $BFSSN = (P, T, F, C, M_0, A, R)$  is the network which meets the following conditions:

(1)  $P = \{p_1, p_2, \dots, p_n\}$  is a finite set of object state libraries. In the spatial sequence model of behavior flow, these libraries indicate the design objects, which constitute the product space, including components of product structure and environmental objects;

(2)  $T = \{t_1, t_2, \dots, t_m\}$  is a finite set of state transitions. In this model, the transition is to describe the action of state transition from one object to another object;

(3)  $F$  is the set of directed arcs between state libraries and transitions, and  $F \in (P \times T) \cup (T \times P)$ . It is used to represent the direction of state transition.

(4)  $A$  is the set of variables which are used to describe some attributes of the state of object state. In the model, each state has more than one attribute, denoted by  $\langle a_1, a_2, \dots \rangle$ , where  $a_i$  is a state variable, which describe some aspect of space state.

(5)  $C$  is the set of state transition functions. Each transition corresponds to at least one transfer function, Transition function is denoted by  $y = C(x)$ , where  $x$  is the source state variable,  $y$  is the target state variable.

(6)  $R$  is the set of connected relationships, corresponding to each transition.

In this Petri net model of spatial state transition of behavior flow, every library corresponds to the state of a component or environmental object. Object space state is described by state variables. Each transition corresponds to the state transition between two objects, and the transition function is used to express the qualitative or quantitative relation for state transition. Sometimes, the changement of states of more than one object is needed to trigger the state change of certain object, so the transition function can have multiple parameters. The transition of spatial state happens through the connection relation between two objects, and each transition relates to one or more connections.

#### 4.3. The Nature of State Transition of Behavior Flow

Product is an organic whole connected with spatial connection relations. In the process of function realization, the states of product space keep on changing, and this kind of changement performs as the transition process from one object to another object, until the final state of product space, which indicates the famishment of function. The spatial connections are the media of the state transition. For each state of an object space, there are some state variables. All of the state variables of an object space are called object state vector, expressed as  $O = [a_1, a_2, \dots, a_n]$ , where  $O$  is a component object or an environment object and  $a_i$  is a state variable.

**Property:** during the transition process of spatial state of behavior flow, each state changement of one object is due to states changement of other objects, denoted as  $[O_1, O_2, \dots, O_{n-1}] \xrightarrow{\text{trigger}} O_n$ , where  $O_i$  is the state vector of an object. All the vectors that make the changement of the state vector  $R_n$  constitute a matrix of states of objects.

The continuous changement of object state is the external performance of behavior flow, while the internal reason of flow is the pass of energy from some objects to other object through the spatial connections, then the energy passion is the nature of spatial state transition. In the mechanical structures, force is the most important form of the energy. In the intake components referred on above, the rotation of cam generates the squeeze force on rod, causing the movement of rod, then rod produces force acting on rocker, which makes the rotation of rocker, and finally the push force of the rocker push the valve open.

#### 5. Spatial Sequence Modeling of Behavior Flow of Engine

The engine is the heart of a car, providing the power for the running of the car, and it is a complex product. The engine is an energy conversion institute, which converts the chemical energy of gasoline and diesel or natural gas into mechanical energy through the working of piston, and the piston is pushed by the force generated by the air inflation of gasoline burning under sealed engine block, and it is the basic principle of the engine. For gasoline car engine, the total function  $F$  is "converting the chemical energy of gasoline into mechanical energy". In this section, the spatial sequence model of engine is constructed with the representation model in section 4.

First, begin the first step of spatial sequence modeling and establish spatial semantic net of engine product. By analyzing connection relations of the components of the engine body



and environment objects, a spatial semantic net of engine product can be constructed, as shown in Figure 5.

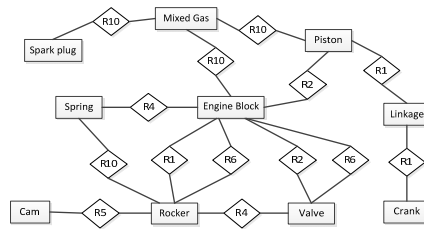


Figure 5. The Spatial Semantic Net of Behavior Flow of Engine

Next, the spatial state transition Petri net of engine is set up. The total function  $F$  of engine can be decomposed into four sub-functions: intake, compression, burning, outtake, and each sub-function corresponds to a behavior flow, named intake behavior flow, compression behavior flow, burning behavior flow and outtake behavior flow respectively. For each behavior flow, the analysis of spatial state transition is conducted separately. The four behavior flow of engine product is described as follow:

BF1 (intake behavior flow): suck the gasoline and air into engine block.

BF2 (compression behavior flow): compress the mixed gas, and make the explosion more powerful.

BF3 (burning behavior flow): light mixed gas to produce mechanical motion.

BF4 (outtake behavior flow): exhale the exhaust gas from the explosion.

For the intake behavior flow, the rotation of cam makes the rotation of rocker around the axis, and then rocker opens the intake valve which contacts with it. After the open of valve, the mixture of gasoline and air enters the engine block, and makes the piston move downward. According to the analysis, set up the spatial state transition Petri net of intake behavior flow, as shown in Figure 6.

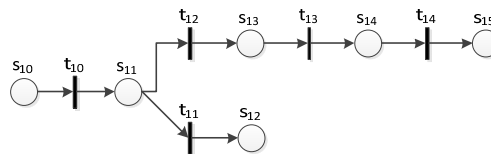


Figure 6. Spatial State Transitions Petri Net of Intake Behavior Flow

For the compression behavior flow, the rotation of crank cause the periodic movement of linkage, then the linkage prompts the co-connected piston moving upward, and compresses the mixed gas. According to the analysis, set up spatial state transition Petri net of compression behavior flow, as shown in Figure 7.

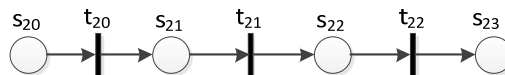


Figure 7. Spatial State Transitions Petri Net of Compression Behavior Flow

For the burning behavior flow, spark plug lights on the mixed gas and cause the explosion, then the inflated gas pushes the piston downward and thus promotes the rotation motion of crank, producing mechanical energy. According to the analysis, set up spatial state transition Petri net of burning behavior flow, as shown in Figure 8.



Figure 8. Spatial State Transitions Petri Net of Burning Behavior Flow

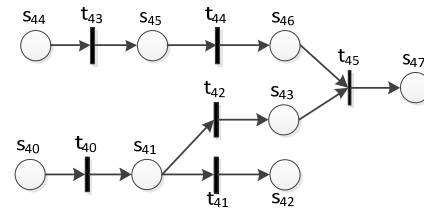


Figure 9. Spatial State Transitions Petri Net of outtake behavior flow

For the outtake behavior flow, the rotation caused the rotation around the axis of outtake rocker, and then the rocker makes the co-connected outtake valve open. Meanwhile, the rotation of the crank promotes the movement of linkage and piston, and then the movement of the piston makes the exhaust gas flowing out from engine block. According to the analysis, set up spatial state transition Petri net of outtake behavior flow, as shown in Figure 9.

At this point, the spatial sequence model of behavior flow of engine product has been completed. With the spatial state transition Petri net, the designers can verify the feasibility of the design.

**6. Conceptual Design with Behavior Flow**

Conceptual design is the process to find a structure solution to meet the functional requirements, and it is the starting point of design. The process of design modeling at conceptual design based on behavior flow mechanism can be divided into two steps: The first step is function decomposition and function to behavior flow mapping, and the second step is get the spatial sequence of design based on the constructed behavior flows, as is shown in Figure 10.

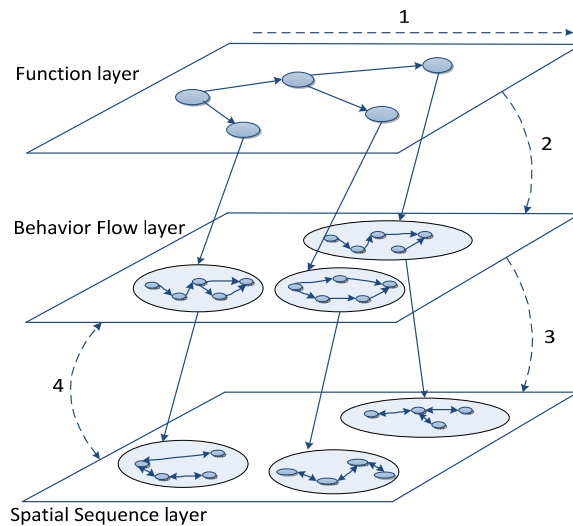


Figure 10. Behavior Flow based Modeling

At the first stage (process 1 and 2), designers need to decompose functions and construct behavior for each sub-function. Function decomposition is to decompose a complex function into independent sub-tasks, to reduce the difficulty of the problem. During the process of function decomposition, specific knowledge of design domain is required, such as design rules of that domain and design experience. According to behavior flow theory, each function can be achieved through a behavior flow. For the construction of behavior flow, there might be

two ways. One method, similarly to the FBS model, is to map the function to a set of behaviors, then order the behavior into behavior flow with series and parallel operation. Another method is to reverse reasoning: the function can be expressed in the input and output flow way, just similar to the input and output flow way in behavior expression, then the reasoning process can start from the output of that function, and get a behavior has the same output, then get the behavior has the output of the prior behavior, until get a behavior flow has the same input and output with that function.

At the second stage (process 3 and 4), the designers map out the spatial sequence corresponding to the behavior flows. According to the input and output relations between behaviors in behavior flow, the appropriate semantic connections can be chosen, then the appropriate design objects can be designed or selected from object library, to construct spatial semantic net and state transition Petri net. Next, keep on design the detail of spatial sequence, such as connection attributes, trigger conditions of state transition and product environment.

## 7. Conclusion

This paper studies the three design variables, function, behavior, structure, and eight design processes of FBS model at first. According to FBS model, product conceptual design is the process that functions maps to behaviors, then the behaviors maps to structure components. Then the representation of behavior is summed up from previous studies, and there exist two main methods, the input and output flow and the state transition network. But both input and output flow method and the state transition method, are limited one independent behavior, and neglected the order among behaviors. A collection of behaviors can be combined into a sequence of behaviors, which is the behavior flow, through the series and parallel operation.

Behavior flow is mechanism of the realization of product function, which requires the orderly execution of behaviors. According to the definition of behavior, behavior is the sequence of physical states changement, so the behavior flow is the state transition sequence of physical structure. Essentially, every behavior is a special behavior flow.

To express this change of structure state, the concept of spatial sequence is proposed in this paper, and the relation among function, behavior flow and spatial sequence is analyzed. Then a representation model of spatial sequence of flow behavior is proposed, and the model parts the spatial sequence into two parts: static connection semantic constitution of product space and dynamic state transition process. Connection semantic constitution is represented by semantic net with joint vocabularies, while the state transition process is described by the mathematical tool—Petri net. Spatial state transition Petri net (BFSSN) describes the conversion relation of states and the mathematical tools can be used to verify the rationality of state transition of product space and the effectiveness of the design.

Finally, based on the behavior flow theory, a conceptual design model is proposed, which first maps the function to the behavior flow, and then maps the behavior to spatial sequence. The model is not complete, the implementation details of the mapping between each two layers is lack, which is the direction of future research of behavior flow.

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