An Extended Causal Behavioral Process Model for Conceptual Mechanical Product Design

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ABSTRACT

In conceptual design, behavior information often plays a pivotal role in mapping from function to structure. Behavioral process is a detailed description of a number of linked sub-level behaviors, which characterize the process of an overall behavior. To understand this process, as well as to provide assistance to designers for design synthesis, it is necessary to construct an appropriate behavioral process model, for which two aspects of design information need to be identified first. One is the characteristics of behavior itself, and the other is the relations between individual behaviors. In this paper, the characteristics of behavior are clarified and the relations of behaviors such as loop relation, temporal relation and state relation together with causal relation are identified. Based on the existing Causal Behavioral Process (CBP) model, an extended CBP (E-CBP) model is proposed by adding these new behavioral characteristics and relations. An Extended BackusðNaur Form (EBNF) representation method is also proposed to represent the E-CBP model. An electric nailing device design case and a lever-clamp assembly system design cases are illustrated to demonstrate the usefulness and applicability of the E-CBP model as well as its representation method.

Keywords: behavioral process modeling, behavior representation, conceptual design.
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1 INTRODUCTION

Since last century, conceptual design has been paid much attention. The goal of conceptual design is to develop a design solution that can fulfill the required functions. To assist conceptual design, it is necessary to identify aspects of design information which might be necessary for design synthesis. For example, function, structure, and behavior are three widely accepted aspects of design information used for the construction of design models. Some other aspects of design information are also proposed, such as input-output flow [1-2], effect-flow [3-4], port ontology [5] and so on. Hirtz et al. [6] have proposed a standardized set of function-related terminology called function basis, which is expanded to a design repository later [7]. Sen et al. [8] have proposed a method based on information theory to check the most useful terminologies of function basis for designers. Van Eck [9] has proposed a strategy that prevents information loss and information change in model conversions between the Functional Basis and Functional Concept Ontology taxonomies.

On the other hand, the inherent relationships between aspects of design information are also essential to construct a design model. The design model determines design knowledge organization and acquisition manner in the design processes. Researchers have proposed many different models to address different design problems [2],[10-14]. For example, Pahl et al. [2] have proposed a functional representation, which provides designers a general understanding of the system and facilitates the automatic design reasoning process. However, such a functional representation model is a high level abstraction of the design, and it lacks representation capability of low level design details [1],[4],[15].

Other design models have been proposed to fill the gap between the high level abstraction and the low level details. For example, Gero [16-17] have proposed the Function-Behavior-Structure (FBS) model. Different from those models where function directly maps to structure, behavior was proposed as the link to bridge the gap between function and structure. The function is transformed into a description of expected behavior, and then the expected behavior is transformed into a structure. By comparing the expected behavior and actual behavior that is derived from the structure, it is possible to gain a final solution through modifying the structure or even the function. The definition of behavior has been changed several times in the past [18].

Similarly, Umeda et al. [19-20] have proposed a Function-Behavior-State (FBS) model. State is represented with sets of entities, attributes, and relations. Behavior is defined as òa sequential one or more changes of statesó. The functions first map to views which represent both behavior and state. The relations between behavior and state are governed by physical laws. With a given state, it can infer the next state. Hence, behavior is considered as state transition of a system. Deng [21] argued that it is just one viewpoint by considering behavior as state transition; for a specific design domain or a specific design problem, other viewpoint may be more helpful. For mechanical design, it is often more suitable to consider behavior as the physical interactions between components of the design as well as between the design and working environment.

Considering the interactions between a design and its working environments, Deng et al. [1],[21] have proposed a Function-Environment-Behavior-Structure (FEBS) design model. The behavior of a product is represented by a Causal Behavioral process (CBP), which is composed of a set of individual behaviors that link with each other by causal relations. Liang and Paredis [5] have proposed a port ontology. Port is defined as the locations of the intended interactions between components; and function, behavior and structure are considered as the attributes of a port. By applying axioms, such as compatibility axiom, it can identify a suitable part that connects with the two ports.

Behavioral process model [1] is a concrete representation of a designõs behavior that fulfills the required functions. To construct a behavioral process model, it needs to identify the behavior relations. Currently, the characteristics and relations of behavior used to construct the behavioral process model are not well developed. For example, the behavior of a product often incorporates not just the state change of each structural component; nor does it only incorporate the interactions between components or between the components and the environments. More often than not, it actually incorporates both of them. In addition, materials play an important role in engineering design. Materials with special functionalities can facilitate the structure design and selecting proper materials might improve product sustainability in the product life cycle [22]. In practice, behaviors of those objects that are not parts of the desired product but are involved in the behavioral process may also need to be considered. For example, exploiting appropriate reagent is usually involved in the design of some testing instruments, as different reagents might lead to different design solutions.

To address these design problems, we propose an extended casual behavioral process model, based on the existing CBP model [1], by exploiting new behavior characteristics and relations. In the following sections, we shall first give a description of our understanding of behaviors, followed by a discussion of the behavior relations. Secondly, an extended behavioral process model is discussed, which is followed by an EBNF-based representation for behavioral process model. Last, an electric nailing device is used as example to illustrate the proposed ideas.

2 UNDERSTANDING OF BEHAVIOR

For design synthesis, behavior is often employed to facilitate the mapping from function domain to structure domain [17]. It is very useful when there is difficulty in mapping a function to structure directly. As shown in Fig. 1, the overall function is divided into several sub-functions. Each sub-function is fulfilled by one or a set of behaviors and each behavior might be performed by a structure. The structures delivering all the necessary behaviors for the required function can then be constructed into a physical product with the assembly relations. Behavior is used as a more concrete level of representation of a system than function. But the term òbehavioró used here is somewhat different than that used in system dynamics [23], where the behavior is associated with the dynamic characteristics of a system and often refers to system dynamic simulation.

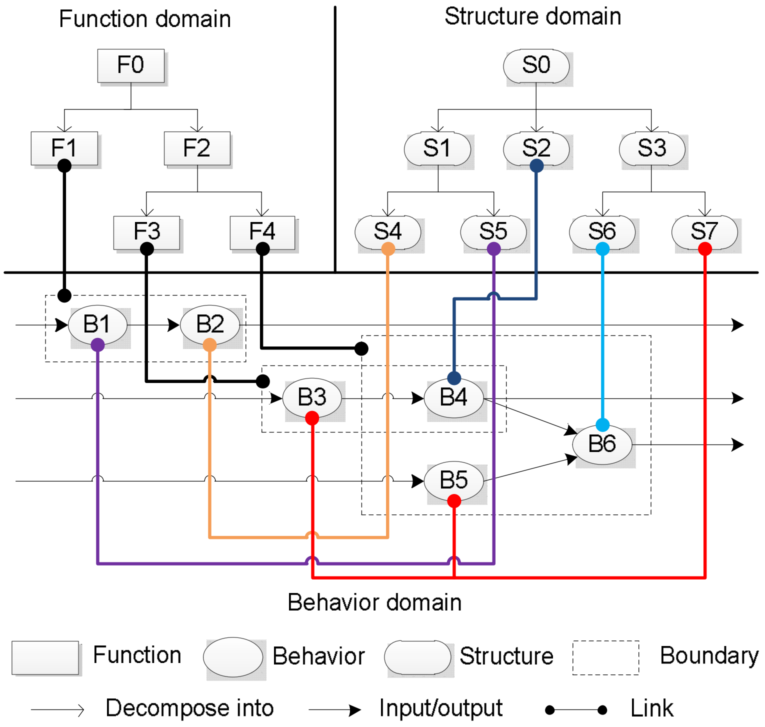


Fig. 1: Function-behavior-structure mapping topology.

However, different researchers have different perspectives of behavior and give it different definitions in different research areas [15], [21]. In this paper, we adopt the perspective that behavior exhibits the characteristic performed by the structure to fulfill the functional requirements [21]. In other words, behavior can be recognized as the physical action performed by the structure or the associated physical state change or maintained by the structure. For example, a spring can store energy by keeping its compressed state and release energy by the extension action.

In practice, a structure can perform more than one behavior at a time, or can perform different behaviors in different contexts. Some of the behaviors are intended; others may be unintended. For example, an internal combustion engine provides the driving force to the wheels and outputs the exhaust gas to environment in the meantime. Obviously, the driving force is the functional output, thus the intended; while the exhaust gas would pollute the environment, hence is a side effect. As a result, we refer to the behavior that generates the required functional output as the intended behavior and that generating a harmful output as the side effect.

3 BEHAVIORAL RELATIONS

In FEBS model, the required function is fulfilled by one behavior or a set of behaviors [1]. Behaviors are not independent, but interact with each other or with the working environment. These interaction relations are essential to combine the individual behaviors into a behavioral process. As such, a good understanding of the behavior relations is indispensable for constructing the behavioral process model.

3.1 Causal Relation

In the work of Deng [21], behavior is abstracted as a process for transforming the driving inputs to functional outputs. These inputs and outputs are characterized by physical parameters, such as position, velocity and force. The relations of these physical parameters are governed by physical laws. That is, the functional output of one behavior could be the driving input of another behavior. The input and output relation of these two behaviors is called causal relation. Behaviors are connected and form a behavioral process to fulfill the functional requirements. Causal relation is the most essential relation of behaviors, because it describes the dependency of behaviors in the behavioral process. In other research, causal relation is usually recognized as **ò**if-then**ó** relation [2] or **ò**effort-flow**ó** relation [3-4].

3.2 Temporal Relation

The intended behavior performed by a product can be represented by a behavioral process which might consist of a set of individual behaviors. The individual behaviors can exhibit simultaneously or one after another. That is, behaviors may have the temporal sequence or concurrency. Additionally, a behavior, such as *store energy*, may maintain its existence for a period.

Temporal relation indicates the concurrency or sequence characteristics of behaviors. When two or more behaviors need to utilize a same energy or material resource, there might be several situations. First, other behaviors may wait until the first behavior has released the resource. Second, a behavior may have to wait until more than one preceding behavior has finished, before it can actually occur. That means the behavior would not start until all the other relevant behaviors have finished. Third, a behavior may generate a functional output to its succeeding behavior and this shall continue for a while. The succeeding behavior would wait for a period before it is to occur. These will be explained in more details in the following sections.

3.2.1.1 Occur before and occur concurrently

In order to determine whether these behaviors occur concurrently or sequentially, we defined two concepts: *occur before* and *occur concurrently*, which are subsets of Allen's temporal interval logic [26].

> “*If behavior B1 starts and finishes before behavior B2 starts, then we say B1 occurs before B2. If behavior B1 occurs before Behavior B2, then we say that B2 occurs after B1. Also, if B1 does not occur before or after B2, then we say that B1 and B2 occur concurrently.*”

As shown in Fig. 2, there are three types of two behavior occurrence order. According to the definition, Fig. 2(a) indicates the sequence characteristic of B1 and B2, and the others indicate the concurrency characteristic of B1 and B2.

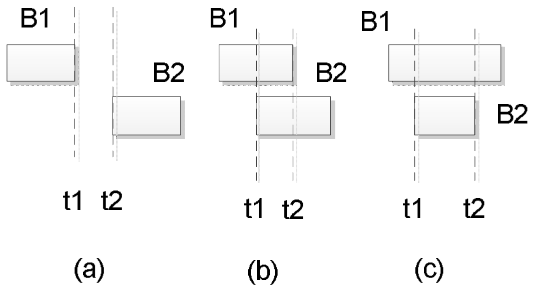


Fig. 2: Three types of two behavior occurrence order.

3.2.2 Utilization

As an important characteristic of behavior, time can be used to measure the efficiency of a product or a system. It is also useful in the analysis of current system or product, and could give constructive advice for design refinement or for the verification of the behavioral process to determine whether it is optimized.

Assume that a required function is fulfilled by six individual behaviors, and the causal behavioral process is represented as shown in Fig. 3. Each behavior would take a certain amount of time to generate functional outputs, which in turn are used to cause the succeeding behavior to occur. If the behaviors are not resources constrained (that means a behavior can occur immediately when the proceeding behaviors have generated functional outputs to it, otherwise it shall need to wait until the same resource has been released by the other behavior), Critical Path method (CPM) [25] can be used to calculate the total cost time of the behavioral process and find the critical path that would cost the most time. With the result, designers can determine whether the behavioral process is optimized and if not, how to optimize. The details can be seen in our previous work [26]. Especially in the concept evaluation stage, if there are two more behavioral processes exhibiting the same functional output, time can be used as an important aspect to evaluate the two behavioral processes.

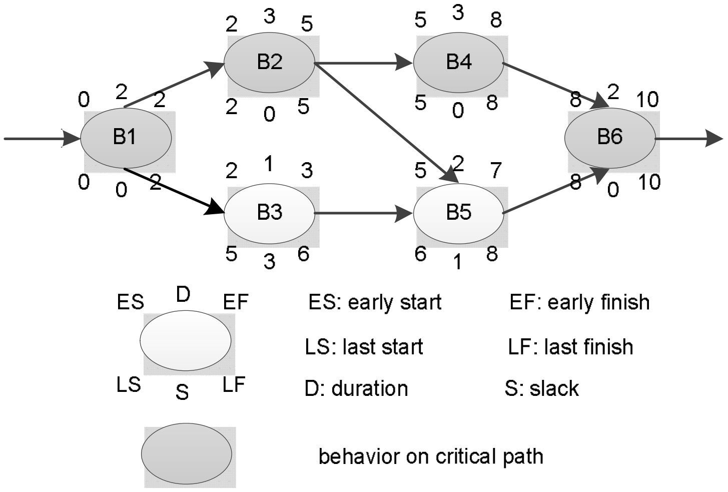


Fig. 3: A behavioral process to fulfill a required function.

In the resource constrained situation, such as when more than one behavior is performed by a structure, or when the input objects can only be processed by the noninterference behaviors, temporal information is also important for design decision making. For example, a work-piece may be processed by several cutters in the same time as long as each cutter works in a non-conflict area. However, these behaviors might not be performed synchronously if they work on the same area. They are performed in sequence or until the previous behaviors have finished. In this situation, the resource-constrained method should be applied, such as resource-constrained critical path method algorithm [27], genetic algorithm for resource-constrained scheduling [28], and phantom float [29], etc.

3.3 Loop Relation

By analyzing the automatic or semi-automatic devices, such as automatic mounting devices, automatic press fitting devices, electric (or pneumatic) nailing devices, etc., we noticed that this kind of devices have a common characteristic in that, all the movable components of the devices will return to the initial state after finishing a certain behavioral process. During this behavioral process, there are two auxiliary functions (hence two auxiliary behaviors): the trigger behavior triggers the loop to occur, and the revert behavior resets the main behavior states. Apart from these two behaviors, the main behaviors are those that are used to deliver the primary functions of the behavioral process. These three behaviors and other internal behaviors form a loop and the revert behavior will connect to the main behavior.

Take the electric nailing device for example, the behavioral process is shown in Fig. 4. There are four loops in process: a virtual overall loop (loop 0) and three sub-loops (loop 1, loop 2 and loop 3). The overall loop represents the behavioral process of one nailing action. The overall loop is called virtual loop as there is no direct way to return from the end of the behavioral process to the start. However, it needs a loop to reset the behaviorsô state to prepare for the next repeated nailing action. As a result, three sub-loops occur causally to construct the overall loop. That is, the effects of the three sub-loops equal to the overall loop. The loop 1 occurs before loop 2, and loop 2 occurs before loop 3. In loop 1, after releasing the force on the switch button (trigger behavior), the switch button will return to its initial position as the spring extends (revert behavior). Together with the main behavior (switch button move down), the three behaviors form a loop. In the meantime, the revert behavior of loop 1 is transformed by internal behaviors to be the trigger behavior of loop 2. As the same, the revert behavior of loop 2 also acts as the trigger behavior of loop 3.

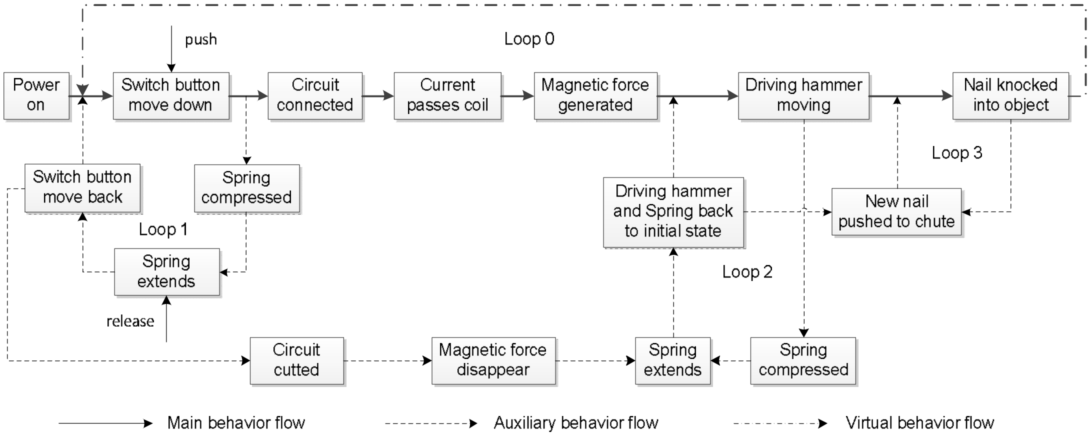


Fig. 4: Behavioral process of electrical nailing device.

In the previous work, we have discussed the rules and laws of loop relation [30].

3.4 State Relation

In mechanical products or systems, one structure could generally perform more than one behavior. For example, the cutter of a lathe may perform feed, cutting, retract or other behaviors under different conditions. These behaviors can be characterized by different states of the structure, which are triggered by different conditions or behaviors performed by other structures. Note that the term òstateó used in this paper is a little different from that mentioned in the Function-Behavior-State design model [20], where the state from the FBS model corresponds to the physical attribute relations of an entity, while in this paper, state can be regarded as a set of some special physical attributes of an entity at some time.

For example, the compression spring has four states: normal state, extremity state, store energy and release energy. The relationships of these four states are illustrated in Fig. 5. It can be seen that the normal state and extremity state are two boundary states, and the store energy and release energy are two intermediate states. In order to change from one state to another, there must be trigger action from other behaviors. In the state change process, it could receive driving input or generate functional output.

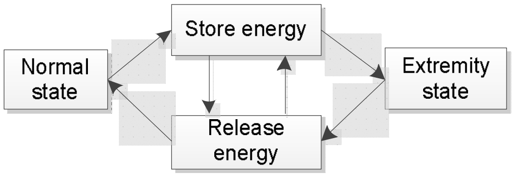


Fig. 5: State transformation of compression spring.

3.4.1 Material state relation

Materials play an important role during the entire design process, especially those new smart materials which can be used to represent complex physical structures to achieve specific functional requirements. For example, piezoelectric material can be used to convert pressure to electricity in some design context. Comparing to a combination structure that consists of both mechanical and electronic components, application of this material can facilitate the design synthesis and make the structure of the design simpler. To represent the behaviors and behavior relations of these materials, state relation can be used. Take the shape memory alloy (SMA) as an example, some structures utilizing SMA can return to the initial state when they are heated up to a certain temperature. There can be two states and these can be transferred from one state to the other when triggered by other behaviors, as is shown in Fig. 6. With the trigger behavior, the material behaviors can connect with other behaviors of the product to form an overall behavioral process.

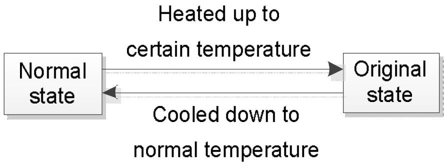


Fig. 6: SMA state transition triggered by other behaviors.

4 EXTENDED CAUSAL BEHAVIORAL PROCESS MODEL

Since behavioral process model connects the functional hierarchy with the structural hierarchy of a design, it is useful to assist design synthesis in conceptual design. It can also be used to analyze the existing systems to get a good understanding of the design intention, so as to improve the design. In this section, we attempt to construct a behavioral process model based on existing CBP (causal behavioral process) model, by incorporating those new aspects of behavior characteristics discussed in the previous sections.

4.1 CBP Model

As one of the existing behavior models, the CBP model proposed by Deng et al. [1] considers behavior as the interactions between the structures, as well as the interactions between the structures and working environment. The intended behavior performed by a product might be exhibited by a behavioral process model which consists of a set of individual behaviors. These individual behaviors are classified as output behavior and internal behavior. The output behaviors are those that produce the productĩs functional outputs and the internal behaviors are those that cause the output behaviors to occur. Hence, the individual behaviors are connected by the casual relations between them. As a result, these individual behaviors form a casual behavioral process.

4.2 E-CBP Model

With the behavior characteristics and relations mentioned above, behaviors not only connect each other with casual relation, but also with the temporal, state and loop relations in practice. As a result, the original CBP model can be extended to be an E-CBP model with these relations, where the letter **ò**E**ó** indicates **ò**extended**ó**. Fig. 7 shows a graph representation of E-CBP. B1-B6 are internal behaviors. B7 is output behavior. B2 and B2ĩ are two state behaviors. They are performed by the same structure when the structure has different states. With the driving input from B1, B2 changes the structure state to another. With the trigger input of B7, B2' resets the structure state and generates a functional output to B6. B3, B4, B5 and B6 form a loop in the behavioral process which might reset the initial state of the mechanism to prepare for repeated action. E1 and E2 are two environment elements. B1-B7 construct an extended casual behavioral process. It can satisfy the functional input from E1 and produce the functional output to E2.

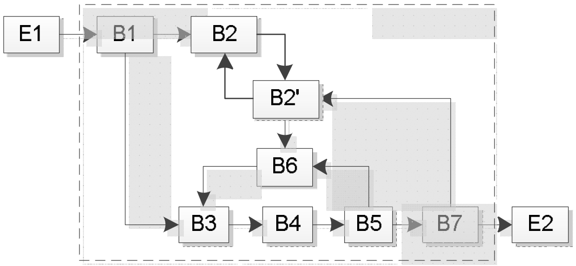


Fig. 7: An extended causal behavioral process graph.

It must be noted that the graph of E-CBP shown in Fig. 7. does not directly represent the temporal relations. It might need a sequence diagram to represent the temporal relations for complement. To describe and utilize these design information and behavior relations, a semantic representation based on EBNF grammar is discussed in the next section.

The steps to construct an E-CBP model are as following.

(1) Identify the behaviors that can fulfill each leaf sub-function in the function tree. That is to say, list all the available behaviors that can fulfill the required function.

(2) Identify the causal relations of behaviors.

(3) Identify the state characteristics and state relations of behaviors if possible.

(4) Identify the main behaviors, trigger behaviors and revert behaviors that form loops if possible.

(5) Identify the time characteristics and temporal relations of behaviors, as well as the constrained resource of behaviors if possible.

(6) Combine the behaviors with functional outputs and driving inputs to form an E-CBP model that corresponds to the sub-function and parts of the design.

(7) Combine all the E-CBP models to form an overall E-CBP model that corresponds to the overall function of the design.

(8) Optimize the E-CBP model with time and loop characteristics or other criteria.

5 EBNF-BASED BEHAVIOR REPRESENTATION

In order to organize the behavior knowledge and develop computer-aided design tools for behavioral process modeling and analysis, it is essential to develop an intuitive and formal representation of the aforementioned behavioral process model, i.e. E-CBP model.

To address this problem, we exploit the object-oriented idea for E-CBP representation. By using this idea, it is possible to represent the behaviors of a product collectively, where these behaviors constitute a behavioral process to fulfill one or more required design functions. This methodology is materialized by the Extended Backus–Naur Form (EBNF) grammars that are used in Go programming language specification [31].

As listed in Tab. 1, the intended physical behavior that corresponds to the required function is composed by a set of behaviors which occur in sequential or simultaneous order. Each behavior consists of behavior name, inputs and outputs, behavior states, time attribute, relationships of the behavior, other behavior attributes, constraints and the structures that can perform the behavior. The inputs of a behavior are the outputs of other behaviors or environment elements that imposed on the behavior. The inputs of a behavior can be distinguished as functional inputs that cause the behavior to occur and harmful inputs that would cause bad effects on the behavior or the structure. Similarly, the outputs of a behavior can be distinguished as functional outputs and side-effects. Behaviorõs states represent all the states of a behavior, including boundary or extremity states and intermittent states. Temporal attribute represents the start time and duration of a behavior. Other attributes can be included as an extensible description of the behavior. Structures are a set of structural components or assemblies that can perform the behavior. Behavior relations are the relationships between the behavior and other behaviors which include the causal relation, temporal relation, loop relation, state relation and other relations. With these relations the behavior and other behaviors can form a behavioral process that fulfills the overall function of the design. Constraints represent the additional conditions that associate with the behavior attributes, the behavior relations and the requirements.

IntendedPhysicalBehavior = SingleBehavior {SingleBehavior} .

SingleBehavior = òBehaviouró ò{ò BehaviorName ò;ó { BehaviorInput ò;ó} { BehaviorOutput ò;ó} {BehaviorStates ò;ó} {TimeAttribute ò;ó} { OtherAttribute ò;ó } { BehaviorRelation ò;ó } { Structure ò;ó} { Constraint ò;ó } ò}ó .

BehaviorInput = FunctionalInput | HarmfulInput .

BehaviorOutput = FunctionalOutput | SideEffect .

BehaviorRelation = CausalRelation | TemporalRelation | LoopRelation | StateRelation | é .

CausalRelation = PreviousBehaviors | NextBehaviors.

TemporalRelation = SucceedingBehaviors | PrecedingBehaviors | ConcurrentBehaviors .

LoopRelation = MainBehaviors | TriggerBehaviors | RevertBehaviors | InternalBehaviors .

StateRelation = StateBehaviors | TrggerBehaviors .

Tab. 1: Behavior representation.

6 CASE STUDY

6.1 Case 1: Problem Description

In this section, an electric nailing device is studied to illustrate the proposed E-CBP model and behavior representation. The device consists of a number of structural components, including coil windings, driving hammer, compression spring, trigger button, nail box etc., as are shown in Fig. 8. The function of the device can be described as òstrike nails into an object quickly and repeatedlyó (F0). It must satisfy two performance requirements - the working time for hitting a nail into an object needs to be controlled in a certain time, and the device needs to reset to the initial state automatically after each nailing action.

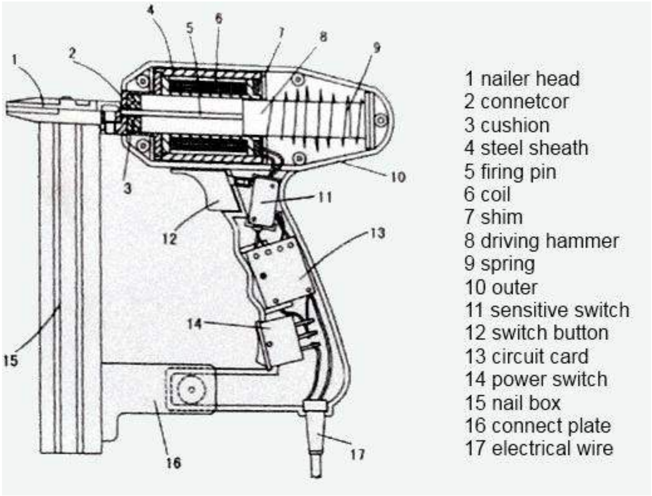


Fig. 8: A sketch of the electric nailing device.

Initialize with functional decomposition to get a function

- F0: strike nails into an object quickly and repeatedly
  - F1: strike a nail into an object
    - F11: generate a large enough force
    - F12: transfer the force upon the nail
  - F2: reset device state
    - F21: reset the driving hammer position
    - F22: transfer a nail

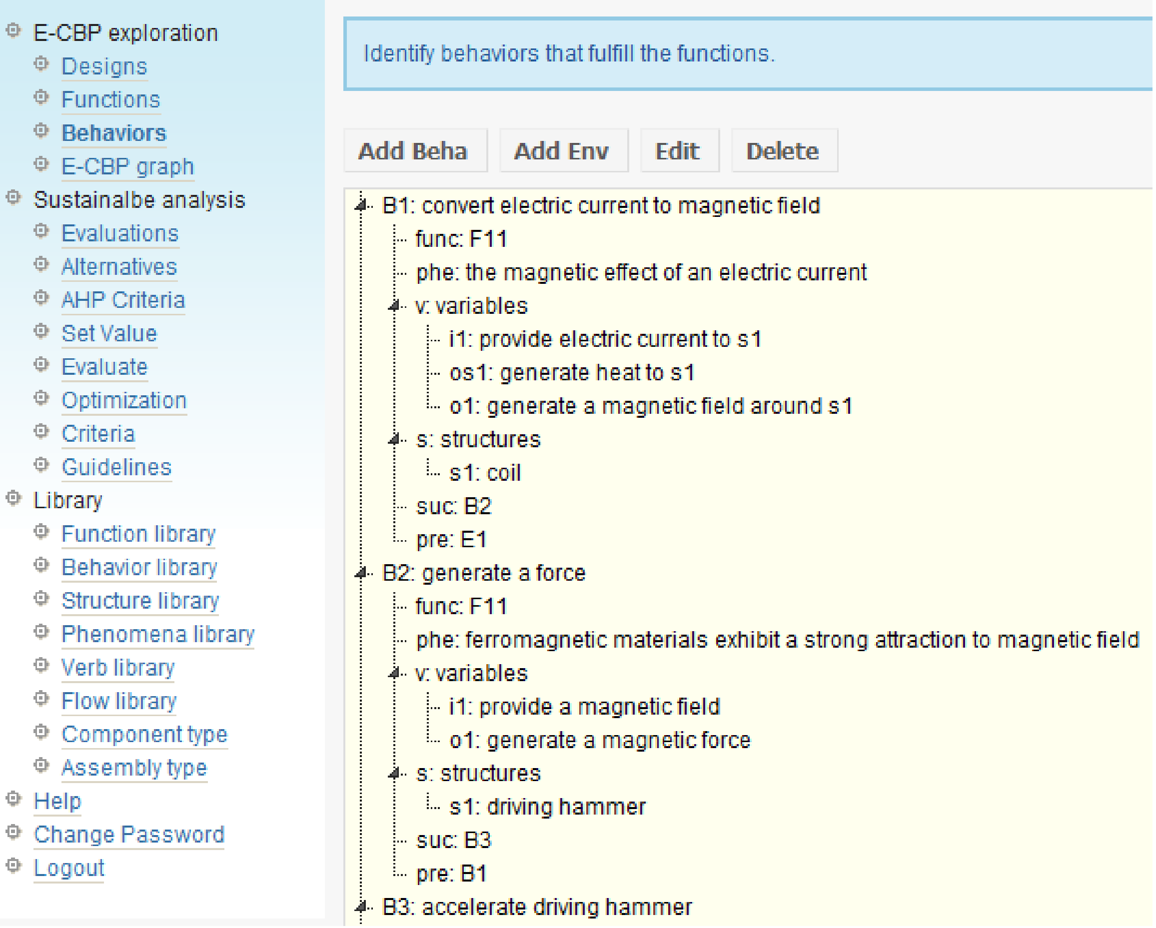
Fig. 9: Function hierarchy of the electric nailing device.

With these design requirements, the main function of the device can be divided into two sub-functions, including òstrike a nail into objectó (F1) and òreset device stateó (F2). Even more, F1 can be further divided into two sub-functions, including ògenerate a large enough forceó (F11) and òtransfer the force upon the nailó (F12). Similarly, F2 can be divided into òreset the driving hammer positionó (F21) and òtransfer a nailó (F22). The functional structure is shown in Fig. 9.

6.1.1 *E-CBP construction*

6.1.1.1 *Identify the behaviors that fulfill the functions*

As discussed above, each function might be achieved by a set of behaviors. Take the ògenerate a large enough forceó (F11) for example. According to electromagnetic effects, the coil would generate a magnetic field when current is passing it. The magnetic field would apply a force on the driving hammer. The magnitude of force is determined by the current and the turns of coil. So F11 can be fulfilled by òconvert electric current to magnetic fieldó (B1) and ògenerate a forceó (B2). The details are shown in Fig. 10. Similarly, F12 can be fulfilled by òaccelerate driving hammeró (B3), òtransfer force to nailó (B4) and òpush nail into objectó (B5).

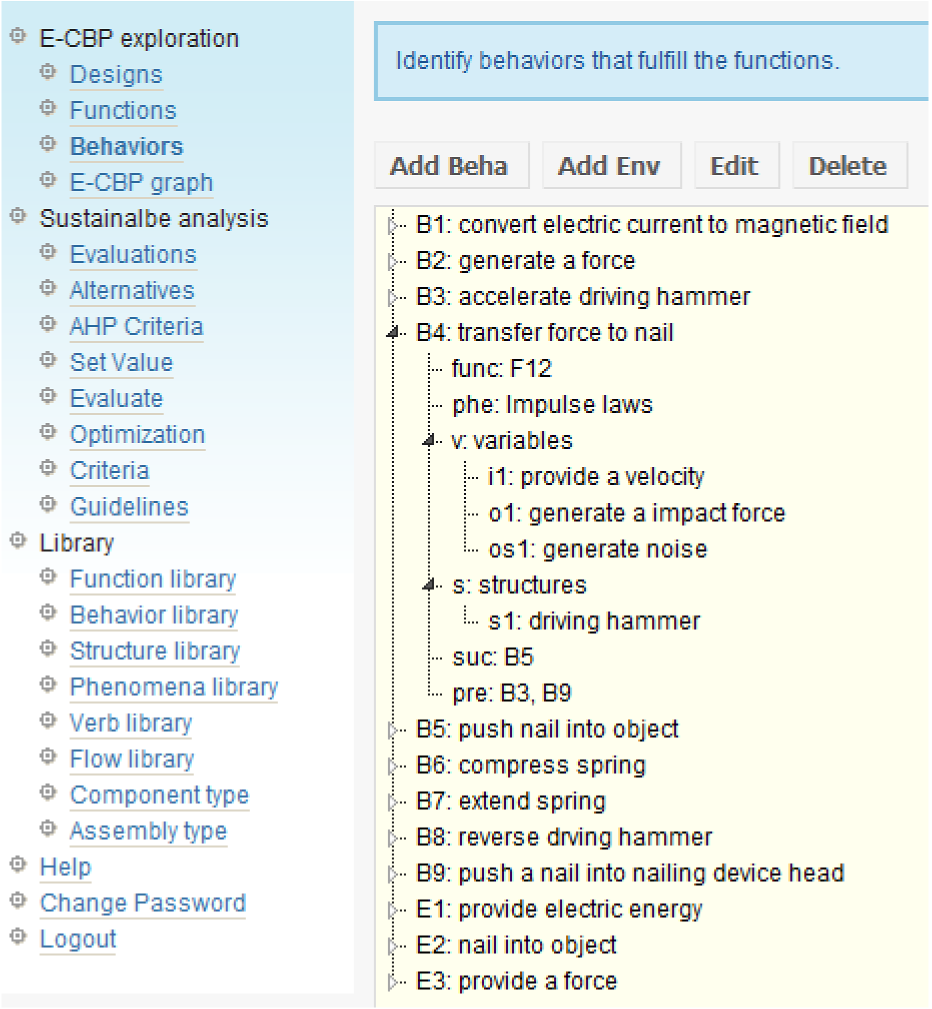


Identify behaviors that fulfill the functions.

- B1: convert electric current to magnetic field
  - func: F11
  - phe: the magnetic effect of an electric current
  - v: variables
    - i1: provide electric current to s1
    - os1: generate heat to s1
    - o1: generate a magnetic field around s1
  - s: structures
    - s1: coil
  - suc: B2
  - pre: E1
- B2: generate a force
  - func: F11
  - phe: ferromagnetic materials exhibit a strong attraction to magnetic field
  - v: variables
    - i1: provide a magnetic field
    - o1: generate a magnetic force
  - s: structures
    - s1: driving hammer
  - suc: B3
  - pre: B1
- B3: accelerate driving hammer

Fig. 10: Detailed information of B1.

Different from F11 and F12, F21 and F22 perform the auxiliary purpose to improve the working efficiency. In order to reset the driving hammer position, it needs to apply a force on the driving hammer in the opposite direction to push it back. To reduce external energy inputs, spring is used as the energy storage mechanism. In the B3-B5stage, the spring is compressed. After B5, spring is released to provide a force. Hence, spring performs as the internal energy storage mechanism. The function of spring can be fulfilled by **ò**compress spring**ó** (B6) and **ò**extend spring**ó** (B7). B6 and B7 can transform from each other. The functional output of B3 triggers the transformation from B6 to B7, and also provides the driving input for the transformation in the meanwhile. Similarly, the functional output of B5 triggers the transformation from B7 to B6, and the transformation generates functional outputs in the meanwhile. So F21 can be fulfilled by B6, B7 and **ò**reverse driving hammer**ó** (B8). Similarly, F22 can be fulfilled by **ò**push a nail into nailing device head**ó** (B9). The detailed information of behaviors is shown in Fig. 11.



Identify behaviors that fulfill the functions.

- B1: convert electric current to magnetic field
- B2: generate a force
- B3: accelerate driving hammer
- B4: transfer force to nail
  - func: F12
  - phe: Impulse laws
  - v: variables
    - i1: provide a velocity
    - o1: generate a impact force
    - os1: generate noise
  - s: structures
    - s1: driving hammer
  - suc: B5
  - pre: B3, B9
- B5: push nail into object
- B6: compress spring
- B7: extend spring
- B8: reverse drving hammer
- B9: push a nail into nailing device head
- E1: provide electric energy
- E2: nail into object
- E3: provide a force

Fig. 11: Detailed information representation of B4.

6.1.2 *Construct E-CBP graph*

After identifying the behaviors that fulfill each sub-function, we need to identify the behavior relations to construct an overall E-CBP graph. For example, B2 generates an output which is the input of B3 (B2 causes the occurrence of B3). However, B3 starts before B2 has finished. So B3 occurs concurrently with B2. The temporal relation of the device is shown in Fig. 12. based on sequence diagram.

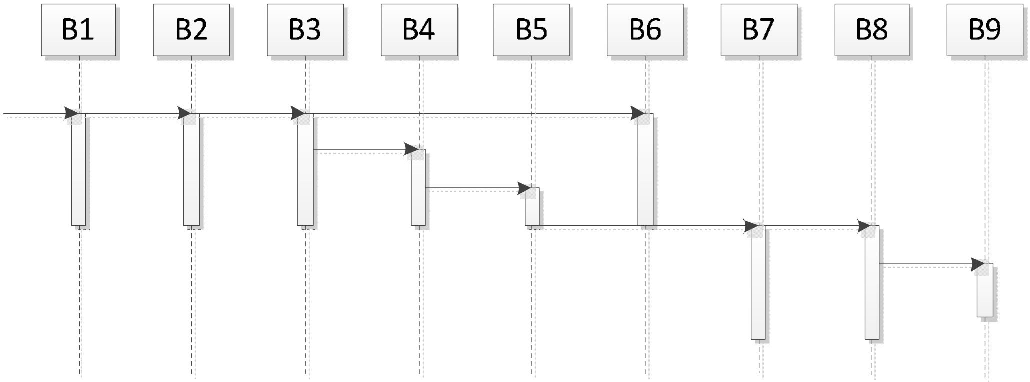


Fig. 12: Temporal relations of behaviors.

Through interactive operation, the overall E-CBP is represented in Fig. 13.

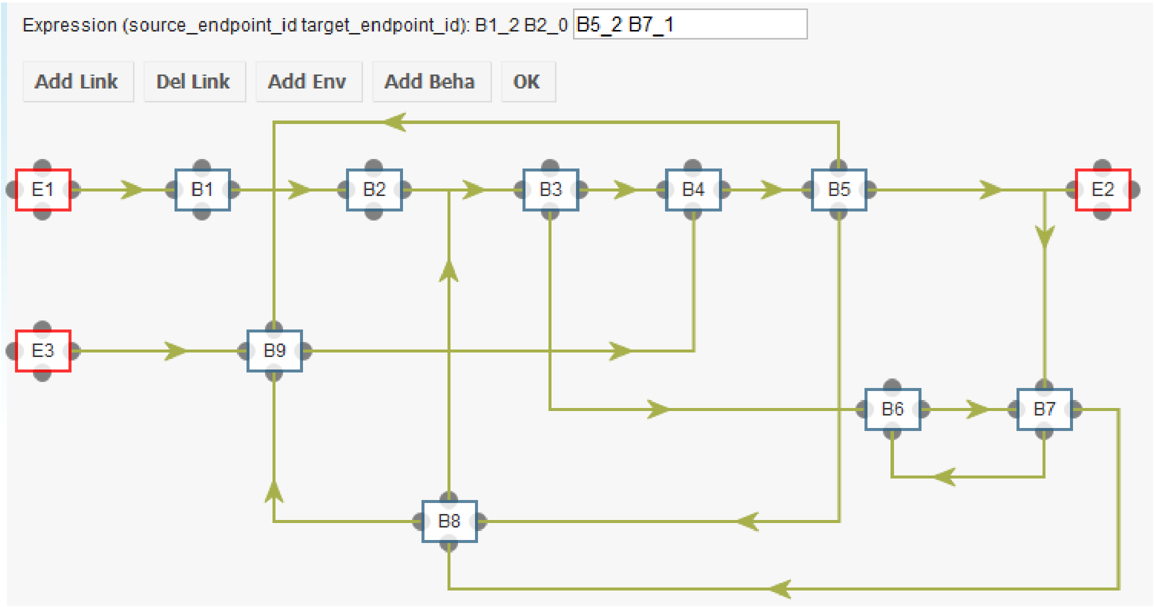
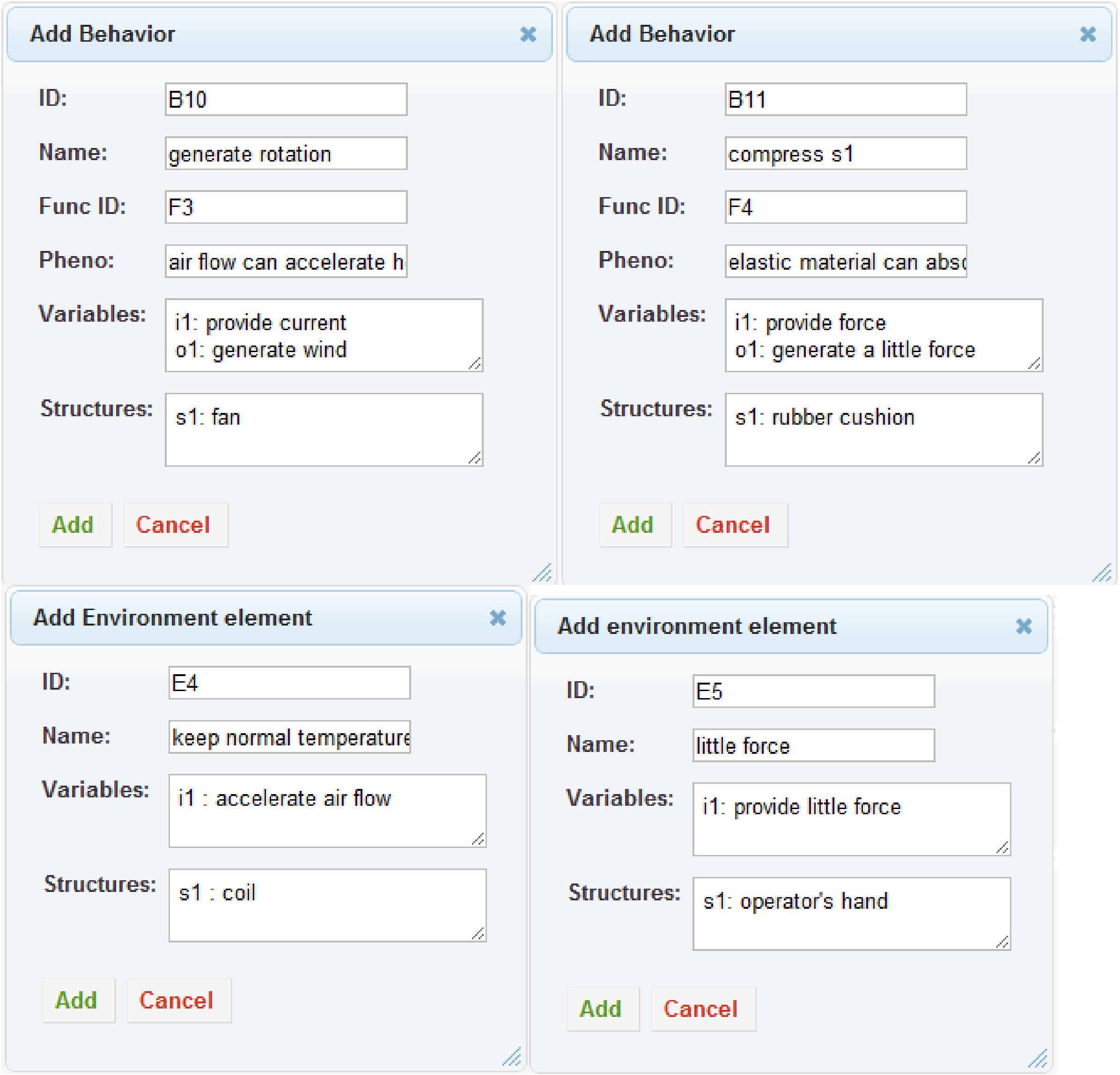

Expression (source_endpoint_id target_endpoint_id): B1_2 B2_0 B5_2 B7_1

Fig. 13: E-CBP graph of electric nailing device.

6.1.3 E-CBP improvements

In practice, we find that there are limitations in the electric nailing device (shown in Fig. 8). First, coil generates huge heat. Second, driving hammer generates huge impact on device housing. According to the E-CBP graph shown in Fig. 13., these two limitations are caused by the side effects of B1 and B8. Considering some physical phenomena, we can find some solutions to fix the problems. For example, fan can be used to cool the temperature of coil and rubber cushion can be used to reduce the impact of driving hammer. The behavior of fan is marked as B10, and the behavior of rubber cushion is marked as B11. The details of B10 and B11, together with related environment elements E4 and E5, are shown in Fig. 14.



ID: B10
Name: generate rotation
Func ID: F3
Pheno: air flow can accelerate h
Variables: i1: provide current
o1: generate wind
Structures: s1: fan

ID: B11
Name: compress s1
Func ID: F4
Pheno: elastic material can abso
Variables: i1: provide force
o1: generate a little force
Structures: s1: rubber cushion

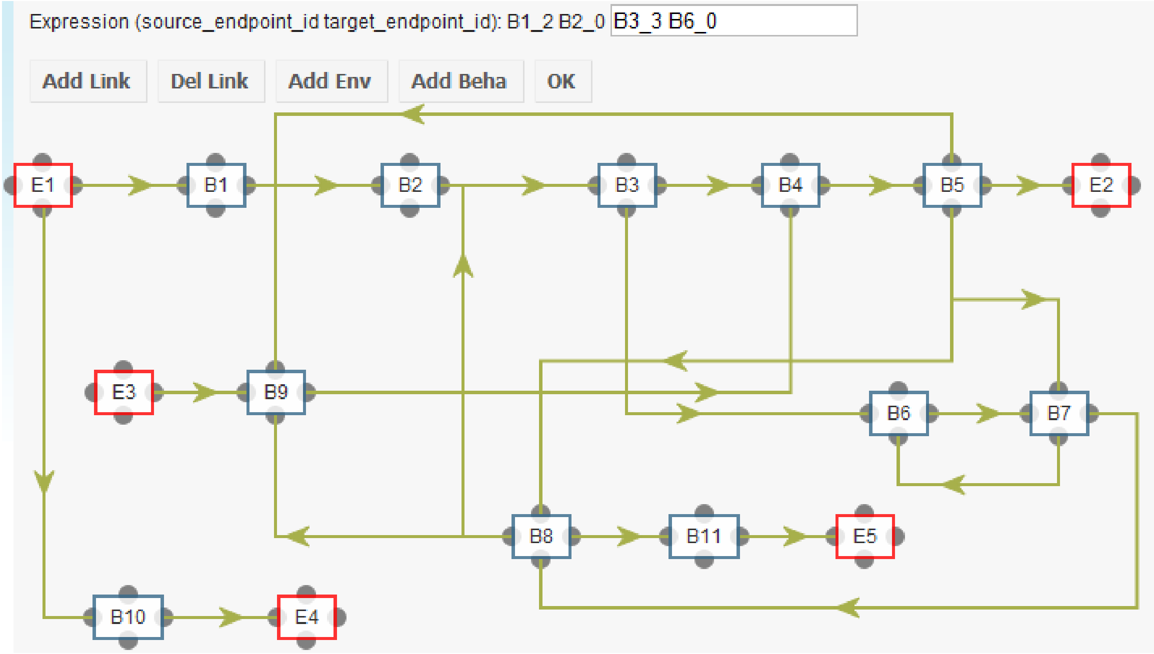
ID: E4
Name: keep normal temperature
Variables: i1 : accelerate air flow
Structures: s1 : coil

ID: E5
Name: little force
Variables: i1: provide little force
Structures: s1: operator's hand

Fig. 14: Details of B10, B11, E4 and E5.

After such modifications, we can get the optimized E-CBP graph, as shown in Fig. 15.

With the E-CBP model, designers can analyze the device or system with temporal [28] and loop characteristics [30] or other criteria in advance, so as to improve the productõs performance or sustainability. Fig. 16 shows the modified electric nailing device.



Expression (source_endpoint_id target_endpoint_id): B1_2 B2_0 B3_3 B6_0

Fig. 15: Modified E-CBP graph of electric nailing device.

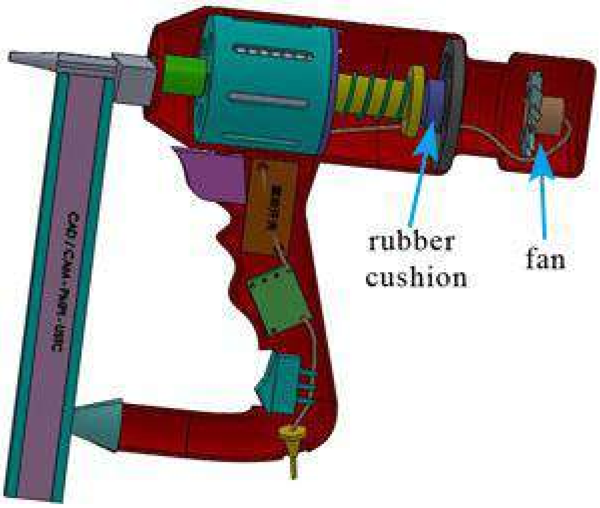


Fig. 16: Modified sketch of electric nailing device.

6.2 Case 2: Problem Description

To further illustrate the proposed methodologies, this section studies yet another design case, which is the design of a lever-clamp assembly system. Fig. 17 shows the basic components of a lever clamp. There are four components in the assembly: component 1 (p1); component 2 (p2); pin (p3) and spring (p4). The product is currently assembled manually, which takes about 10~12 seconds per product. In order to improve the assembly efficiency, an assembly system should be designed. The design goal is to reduce the assembly time to less than 7 seconds per product.

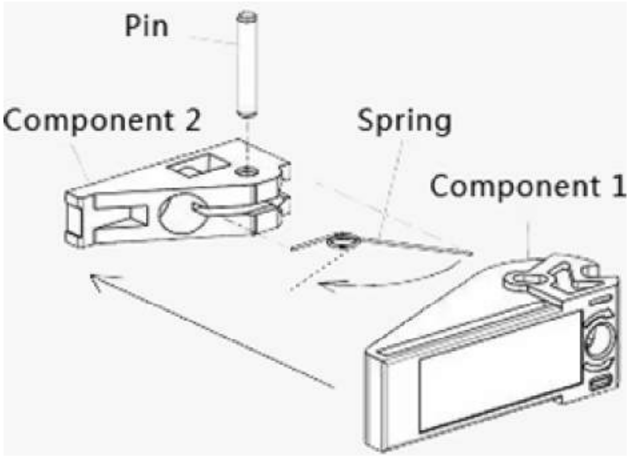


Fig. 17: The exploding view of a lever-clamp.

6.2.1 E-CBP construction

By applying the E-CBP model, the existing manual assembly behavioral process consists of the following individual behaviors: B1 (take p1), B2 (fix p1), B3 (take p2), B4 (fix p2), B5 (take p4), B6 (fix p4), B7 (take p3), B8 (fix p3) and B9 (push p3 into the hole to connect p1, p2 and p4) (The detailed information of each behavior is exempted for brevity). Each duration of B1, B3, B4, B7, B9 is 1s; each duration of B2, B4, B6, B8 is 1.5s. Fig. 18 illustrates this E-CBP graph.

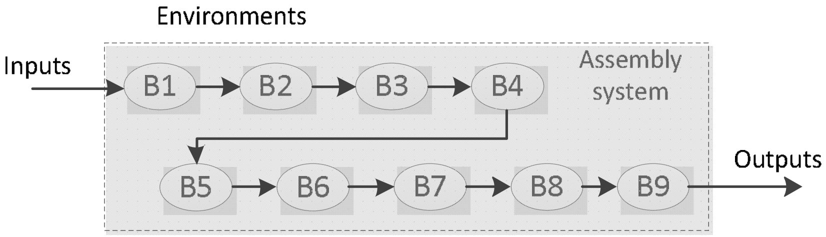


Fig. 18: E-CBP graph of the existing manual assembly system.

6.2.2 E-CBP improvements

By applying the CPM [25], we propose to convert the E-CBP graph to CPM network for design evaluation. This is done by adding the duration time of each behavior into the E-CBP graph. From Fig. 18. it is easily seen that there is only one path, hence this is the critical path of the converted CPM network. The total duration is 11s. From the problem description, this assembly approach doesn't meet the design requirements. In order to reduce the assembly time from 12s to 7s, the CPM network is adapted to reduce the length (i.e. time duration) of the existing critical path. This may be achieved by executing some activities, thus behaviors, in parallel.

A thus-modified E-CBP is shown in Fig. 19, where B1, B3, B5, B7 can be operated by an automatic material feeder. There are four paths in the CPM network, and we can easily find the critical path, given that the duration time of each behavior is known from the design concept. B1->B2->B4->B6->B9 is the critical path and the total time on this path is 6.5s. The efficiency of the assembly system is improved with 41%.

Furthermore, the new assembly system design can be further improved by reducing the duration of behaviors B2, B4, B6 and B9. In the other words, if the duration of these behaviors canȇt be reduced, they become the bottleneck to improve the system efficiency. Designers shall need to find other design solutions.

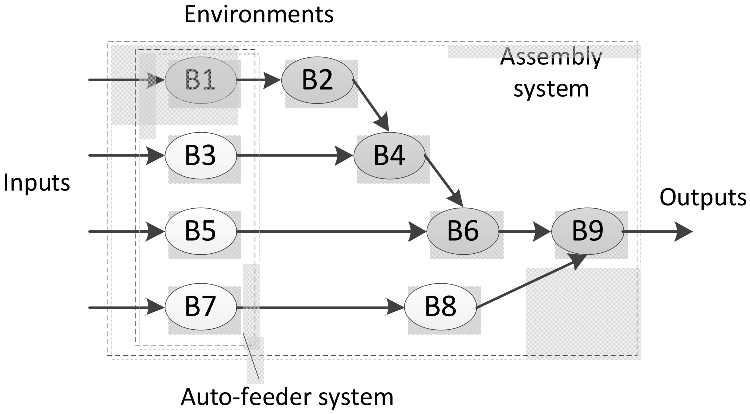


Fig. 19: Improved E-CBP graph of lever-clamp assembly system.

7 CONCLUSIONS

Aiming at a more general and comprehensive behavioral process model, the previous sections have presented a detailed study of behavior characteristics based on the previous work, and the inner relations of behaviors have been discussed. These include the causal relation, temporal relation, loop relation and state relation.

Causal relation is the fundamental relation, which indicates that a preceding behavior would cause its succeeding behavior to occur. Temporal relation indicates the behavior sequence and resource utilization. For some of the design cases, temporal relation not only determines the efficiency of a product or system, but also indicates the performance bottleneck of a product or system to be further improved. Loop relation indicates the periodical behaviors of the components or the product or the feedback of the succeeding behaviors to the preceding behaviors. Designers should follow the rules and laws of loop relation to obtain performance improvement. State relation indicates that one behavior could have more than one form in different process or situation, such as the behavior of materials that are engaged in the behavioral process. These forms can be changed from one to another when triggered. State relation can be used to simplify the behavior analysis of some special structures, such as spring, smart materials based component.

Based on the identification of behavior characteristics and behavior relations, an E-CBP model was proposed. By taking into account the design knowledge organization and multidisciplinary design problem, a uniform behavior representation based on EBNF is proposed. The representation could be easily understood by humans and computers.

Research on the behavior relations and the E-CBP model have enhanced the behavioral process modeling process and provided an insight view of behaviors. In the future, more behavior relations may be explored and added to improve the behavioral process model. Knowledge organization, exploration and reasoning functions will be developed to assist the designers as well.

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