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A Symbiosis-based Functional Reasoning Model for Original Design

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Abstract

Understanding how functional reasoning proceeds is crucial to further establish computer-aided tools for conceptual design. Enlightened by the symbiosis-based evolution theory of organism, this paper proposes a symbiosis-based functional reasoning model for original design, which is based on three kinds of symbiotic relations between product functions. The functional reasoning process of a wood stick-separated device then demonstrates that the model is valid.

Keywords: Functional reasoning, original design, innovative design, conceptual design, symbiosis

1. Introduction

Conceptual design of technical artifacts mainly deals with two tasks: one is generating a functional structure for a desired artifact, e.g. functional reasoning; the other is searching for solutions to the functions of the functional structure, e.g. function-solving [1]. Therefore, the critical issue confronted by computer-aided conceptual design is to construct reasonable knowledge representation and reasoning models for intelligent design systems. Pahl & Beitz argue that there are corresponding relations between function, effect and solution principle [1]. Based on this viewpoint, Feng et al proposed in turn the design catalogue model [2] for the representation of design solutions and the artifact gene (also called analogical gene) model [3,4] for bridging the gap between function and solution to address the issue of function-solving. In addition, Gero proposed the FBS (Function-Behavior-Structure) model to address this issue [5], which is also widely accepted by design society. However, no systematic research has covered functional reasoning in the past decades.

To realize computer-aided functional reasoning, it is indispensable to have a deep insight into the functional reasoning process, e.g. how functional structures are established during conceptual design. In routine design, functional decomposition, proposed by Pahl & Beitz [1], can usually be employed to establish the functional structure of an existing artifact. Functional decomposition, in its essence, can be regarded as reuse of extant design cases. However, during original design, neither sub-functions nor their combinatorial relationships are known to designer [1]. Therefore, exploring how functional structures are constructed in original design is the key to understand functional reasoning process. Nevertheless, at present, researches on this issue are far from systematic. The existing models are mainly combinatorial models based on limited state space, such as the behavioral reasoning model [6] proposed by Welch & Dixon (1994), and the solution unit synthesis model [7] by Chakrabarti & Bligh (1994, 1996), etc. When no suitable solutions can be directly found for a purpose function from the existing knowledge base, these models can then combine multiple solutions in sequence to form a combinatorial solution for the purpose function. This process can be treated either as a functional reasoning process, or as a function-solving process.

Intuitively, the functional structure of a complex technical artifact is formed through combining multiple functional modules. The theory of evolution discloses that complex organisms come into being partly through the symbiosis-based combination of prokaryotic organisms, which means that the functional structure development of technical artifacts resembles the evolution of organisms in the form. Therefore, it is possible to employ the symbiotic evolution theory of organisms to explore the evolution processes of functional structures of artifacts.

2. Symbiosis theory and functional structure evolution

Symbiosis is a kind of relation between species of organisms, which means that two or more species of organisms live together to be better adapted to living environment [8]. Endosymbiosis means that a species lives in the body of another species. The endosymbiosis theory, widely accepted by the current researchers of evolutionary theories, argues that more than one billion years ago, some big prokaryotic cells swallowed some small ones in the original ocean, which occasionally were not digested and then evolved into the organs of the big cells [9]. The widely existing chondriosomes in eukaryotic organisms can demonstrate this theory [9].

It is generally agreed that the predecessors of prokaryotic organisms were heterotrophic ones, living in a circumstance without oxygen. The occasional generation of cytochrome *c*, played a key role in the evolution of atmosphere. It made some tiny organisms possible to produce oxygen through photosynthesis. Oxygen, on one hand made it possible for those bacteria living on oxygen to survive, and on the other hand formed ozone, preventing some cosmic radials, which are necessary energy supply for the predecessors, from getting into them. On this condition, some big cells, which had swallowed bacteria but hadn’t digest them, survived in that they could get energy from the bacteria in their bodies; at the same time, these bacteria also obtained necessary nutrition from those big cells. Therefore, symbiosis had played a crucial role for the generation of today’s complex eukaryotic organisms in the evolutionary history. Through symbiosis, organisms have not only adapted themselves to the environmental change, but their functions have also been improved and complicated.

The researches on artifact gene [3,4] show that design solutions are similar to the organism protein, which also has specific functions. Because a design solution is also the matter carrier of its artifact gene, it is also comparable to a simple organism with a simple function, e.g. a prokaryotic cell. And because social need environment determines whether the complex artifact corresponding to a functional structure can survive in the competitive market, it can be treated as the living environment of artifacts. Thus, the functional structure development process of an artifact can also be regarded as a symbiosis-based evolution process: A function and its solution continually ally with other functions and their solutions to form the symbiotic relations between them in order to be adapted to the changes of customer needs, which makes themselves and those functions together with their corresponding solutions survive in the new customer needs.

The functional structure development process of a car can demonstrate the above symbiosis-based evolutionary process. Initially the main function of a car is to transport passengers and goods; with the increase of car speed, the function of absorbing shock has been integrated in the car's functional structure. Today, no car without a shock-absorber can be found in the market; on the other hand, a shock absorber can't survive independently. With the technical progress, a kind of entertainment function appears together with its carrier of musical equipment. Then the car, acting as a kind of big cell, swallows the small musical equipment. Through supplying passengers with the entertainment function, car has obtained stronger competitive ability, while musical equipment has also occupied bigger market. The functional structure of cars continues to evolve, resulting in that many new functions are integrated with it, such as the function of regulating temperature with the carrier of air conditioner, the function of keeping safe with its carrier of safe air chamber, etc. The whole process is shown in figure 1. Therefore, the functional structure development process of technical artifacts can indeed be regarded as a symbiosis-based evolution process.

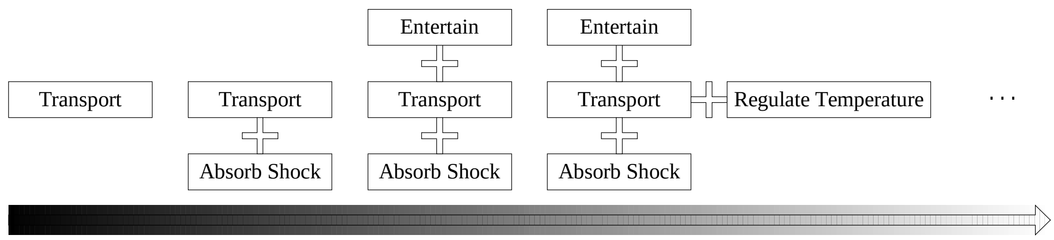

Figure 1. The functional structure evolution process of a car

However, there is also slight difference between these two symbiotic evolution methods. Prokaryotic organisms lived in the original ocean, so they could come together through autonomous movement to symbiose with each other. Nevertheless, design solutions are not creature, so neither can they feel the change of outer customer needs, nor can they move freely to combine themselves with other solutions. Therefore, function symbiosis in design process needs the help of designer, and the symbiotic process can be regarded as happening in the mental ocean of designer.

3. Classification of symbiosis models

The symbiosis models of organisms can be classified as cooperative symbiosis, mutualistic symbiosis and disjunctive symbiosis [8]. Among them, the former two models are similar to the functional structure evolution of artifacts. Cooperative symbiosis means that although both organisms can benefit much from symbiosis, they can also live independently. In the functional structure of an artifact, such symbiosis can be regarded as the free combination of multiple functions originating from different customer needs. For example, the entertainment function and the transportation function of a car can be regarded as this kind of symbiosis. In the product development process, functions of this kind of symbiosis relation are often independent of each other, and VE (Value Engineering) is usually employed to determine what functions should be combined in a future artifact to cater for different customer needs.

Mutualistic symbiosis refers to the dependent relations between two organisms, which means that these two organisms rely on each other. In an artifact, it represents some necessary and objective relations between functions. The relation between the functions of absorbing shock and transportation of a car can be regarded as such kind of symbiosis. In the functional structure evolution process based on this kind of symbiosis, the relations between functions are compact and deducible. Therefore, the functional reasoning model based on the mutualistic symbiosis will be primarily studied as follows.

In the mutualistic symbiosis model, there are 3 kinds of relations between host organisms and guest organisms. Accordingly, such relations are also found in the functional reasoning process after a deep insight is given into the relations between artifact functions. Because the functional structure evolution mainly aims at improving the competitive abilities of host products, the relations disclosed here will be elaborated in the viewpoint of how guest organisms or products contribute to improving the competitive abilities of host organisms or products.

3.1 Supplying necessary conditions

The most common contribution guest organisms make is that they supply host organisms with nutritious substance and energy, which are their indispensable living conditions. Therefore, they supply the necessary conditions required by host organisms. For example, when bacteria evolved into chondriosomes, they provided host organisms with energy. Such kind of symbiosis relation also exists in the functional structure evolution process. Most design solutions need some energy to achieve their functions. For example, when audion works, it needs the necessary base voltage (condition), which，for instance，can be provided by a battery. Here the battery supplies the necessary condition to audion so that it can function properly, e.g. enlarge current. The whole relation can be seen in figure 2. Note that not all solutions need some conditions to work. For example, a slider-crank can convert a rotation into a translation without any conditions, as long as it is properly mounted.

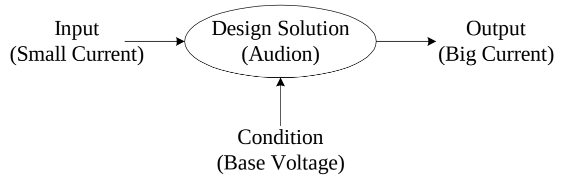

Figure 2. A symbiotic relation based on supplying conditions

3.2 Removing the results of adverse behaviors

The second kind of role guest organisms play in the host organisms is to remove the results of adverse behaviors generated by the hosts themselves. The most common adverse behaviors could be side effects, which, as able to be inferred from their names, are often accompanying effects of main effects. For example, muscle cells will produce a large amount of heat as they move. If the heat were not got rid of in time, it would harm the organisms. It is the sweat gland cells that do the work. In the product development, designer is also confronted with the same problem. When he designs a computer, he will have to determine whether the heat generated when it is computing will do harm to the computer. This is why the electrical fan comes into the functional structure of computers.

There is another special kind of adverse behaviors. On one hand, they contribute to the organism functions, but on the other hand, their action results can't be accepted by the inner environment of organisms, e.g. violate the environmental constraints. Such results will have to be further processed. The way that organisms metabolize amino acid can show this kind of behaviors [10], as shown in figure 3. When some enzyme gets rid of amido from the acid, it converts amido to ammonia, which can do harm to the nerve system. To get rid of its toxicity, some other kinds of enzymes further convert it into carbamide, which is harmless to organisms. Different from side effects, the first enzyme contributes to the process of separating amido from the acid, although it also produces harmful ammonia. The theory of evolution argues that, the numerous kinds of enzymes of an organism probably originate from the swallowing effects of big prokaryotic organisms, through which these enzymes of other organisms came together in the big organisms, and furthermore, the genetic matter (DNA) of the swallowed organisms are integrated with the big organisms, resulting in that their enzymes can be produced by the big organisms [9]. Therefore, it is also a special form of symbiosis.

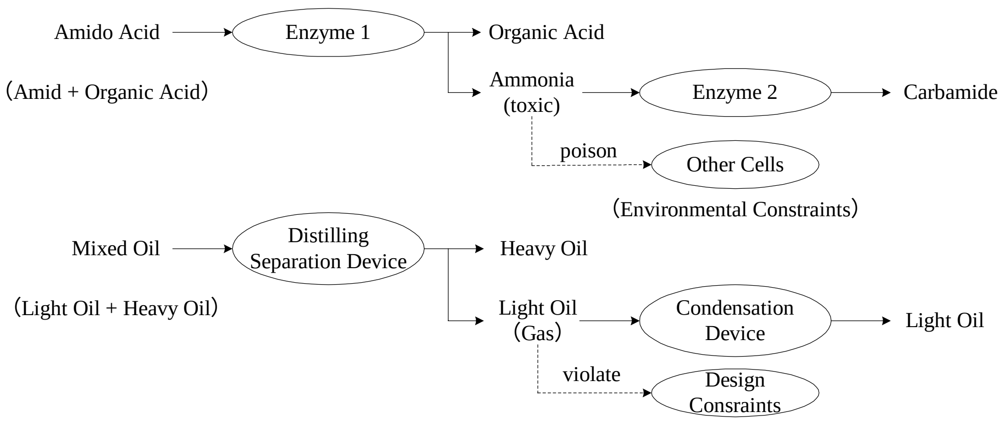

Figure 3. A symbiosis-based evolution model for removing adverse behaviors

This special symbiosis also exists in the functional structure evolution of artifacts. If amido acid is viewed as a special mixture of amido and organic acid, the above process of separating amido from amido acid can be regarded as a kind of separating process. And enzyme, a kind of protein, is similar to a design solution according to the research on artifact gene [3,4]. Additionally, the requirement from the inner environment of organisms on the outcome of the process can be treated as a special design constraint. Thus, the above process is similar to the process of separating mixed oil in the chemical engineering, as seen in figure 3. When the distilling separation device separates light oil from the mixed oil, it is inevitable to convert the light oil to gas. However, such state (gas) of light oil is not suitable for its preservation and transportation in the future. Therefore, the result violates the design constraint on the state of oil. Similar to that some other enzymes are employed to smooth away the unacceptable ammonia, a condensation equipment is appended to the artifact. So its functional structure evolves into a more complex one.

Gero argues that the behaviors of a design solution can be classified as expected behaviors and unexpected behaviors [5]. For example, the expected behavior of CPU of a computer is to compute; however, it also generates a large amount of heat during computing, which is an unexpected behavior. Adverse behavior, in its essence, is unexpected behavior. However, not all unexpected behaviors are adverse. Whether an unexpected behavior is an adverse one largely depends on concrete design constraints. For example, when lathing a work-piece, no additional cooling device is needed if we don’t care the heat distortion of work piece, as long as the lathe can bear the heat.

3.3 Smoothing away environmental influences

To function properly, host organisms need to keep its inner environment stable, which is just the functions of some guest organisms. A typical example is the carrier protein, which selectively transport some material while refusing other materials to enter the host organisms. Just as enzyme, the existing way of such protein in host organisms can also be regarded as a special form of symbiosis, whose corresponding DNA has been integrated with the host DNA. This kind of symbiosis is also very typical in the product development process, which is the main way in which auxiliary functions come into the functional structures of artifacts. Isolation is the most often used function. For example, designer often use shield to prevent unexpected input signals in environment from getting into systems. Another example can be that designer often seals gear cases to prevent dirt from getting into them to influence their working performance. When isolation can’t smooth away unexpected environmental input, it is inevitable to append other new function modules to process the unexpected input. An example is the function of car’s absorbing shock. Another example is the supporting function, which is used to smooth away the input of gravity from the earth.

4. A functional reasoning model based on mutualist symbiosis

Based on the functional symbiosis relations summarized above, a functional reasoning model, e.g. a functional structure evolution model is proposed in figure 4. The functional reasoning model is divided into three branches. First, when the needed condition of a design solution doesn’t match the existing condition, a new function is then needed to fulfill the transformation from existing condition to needed conditions. Then when the results of unexpected behaviors violate design constraints, new functions are imported to further process these results so that they can obey the constraints. At last, the environmental influences are taken into consideration.

The function-solving process enclosed with broken line in the figure is the specification of the function-solving block of the functional structure evolution process. Usually, a function is solved with the case-based solving method at first; if fails, the function is then solved with the combination-based method, e.g. some of existing design solutions are combined step by step to fulfill the desired purpose function. Here the state space-based combinatorial method is often used. Therefore, defining the state space is a key to combination-based function-solving method. The intelligent solving models [6,7] are all based on this logic.

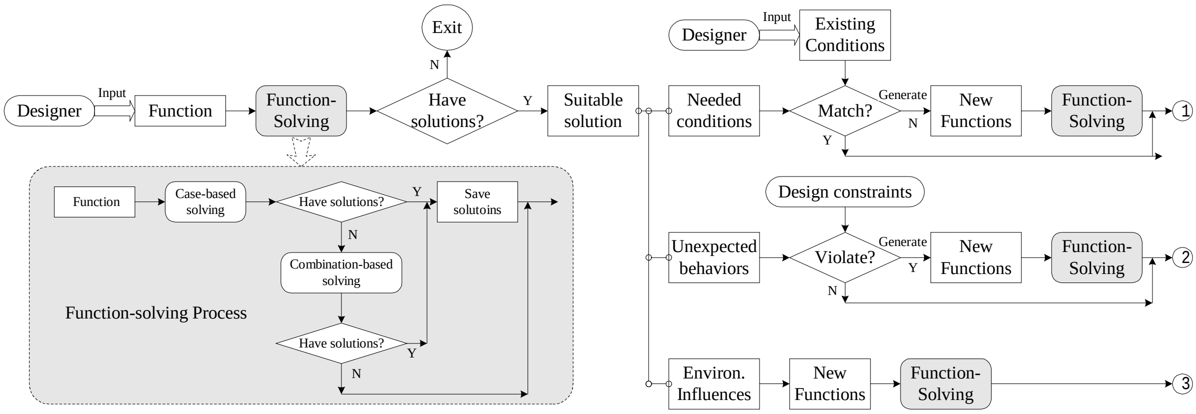

Figure 4. The symbiosis-based functional structure evolution model

Some points about the functional reasoning model should be mentioned here. First, the functional structure evolution process is recursive. That is to say, when new function requirements are disclosed and solved, their solutions are possible to have new conditions and adverse behaviors and to be influenced by environment. Such new factors will further drive the evolution process of the functional structure. Secondly, the evolution process described in this figure only shows the roughly evolving direction of functional structures, and the possible iteration in the design process has been temporarily ignored. Thirdly, in the symbiosis-based functional reasoning model, the functional structure evolution process and the function-solving process intersect and almost happen concurrently, which is different from what Pahl & Beitz argues.

In this model, the method for disposing the unexpected behaviors that violate design constraints, e.g. adverse behaviors, is completely different from the PCM (Propose-Critique-Modify) methodology [11] proposed by Chandrasekaran. The PCM Methodology tries to search for the source of failure from the design solution itself, while the method proposed in this model is to append new function modules to solve the failure of design solution, when it is applied to a new design problem and fails, which will results in the evolution of functional structure. For example, PCM methodology will probably argue that the failure of bearings results from their too small sizes, which further make them overheated due to too high pressure, and the corresponding solution will be the change of the bearings with bigger sizes, as described by Goel [12]; however, the method proposed in this paper will examine the direct failure source and find that the direct reason is that the bearings are overheated, so the solution will be to append a cooling device to prevent them from being overheated. When the failure source of a design solution doesn't come from its inner cause, for example, from the change of design constraints, PCM then can't be employed to solve the incorrect behaviors. In this case, appending new functional modules to correct the incorrect behaviors is necessary. Therefore, the symbiosis-based functional reasoning can be regarded as the PCA (Propose-Critique-Append) method.

5. Application

The conceptual design process of a machine for separating wood sticks is given here to illustrate the above functional structure evolution model. Note that because there are almost no other environmental influences except gravity, they are ignored in this example.

Wood sticks are the main components of toy bricks. After studying the toy brick market, a company proposed the need of machining a kind of column sticks (*l=42mm*, *d=12mm*) massively. After the desired machining speed (about 4 pieces/sec), maneuverability and ergonomics are carefully considered, the input stick stacks are put in 3 layers and each layer includes 20 sticks. Because each time only one stick can be machined, sticks should be separated from the stacks one by one. Therefore, one of the purpose functions here is to separate sticks, which is also what is studied below.

Using case-based solving method, a solution can be obtained for the purpose function, which is often used to separate straws in cafeteria, shown in figure 5(a). This solution needs up-and-down translation (UD translation) to achieve the desired function; however, designer can only supply electrical energy (Alternating Current, AC). Therefore, a new function of transforming AC to UD translation is generated, which can be fulfilled by the combination of an electromagnetic device and a resetting spring. Analyze the unexpected behaviors of the solution. When the stick stack vibrates in a relatively high frequency, the stick sequence in the stack will be destroyed, which can make sticks blocked at the output position. Because this unexpected behavior is very difficult to be disposed, this solution is then rejected. Since no other solution exists, combinatorial strategies are used here to solve the function.

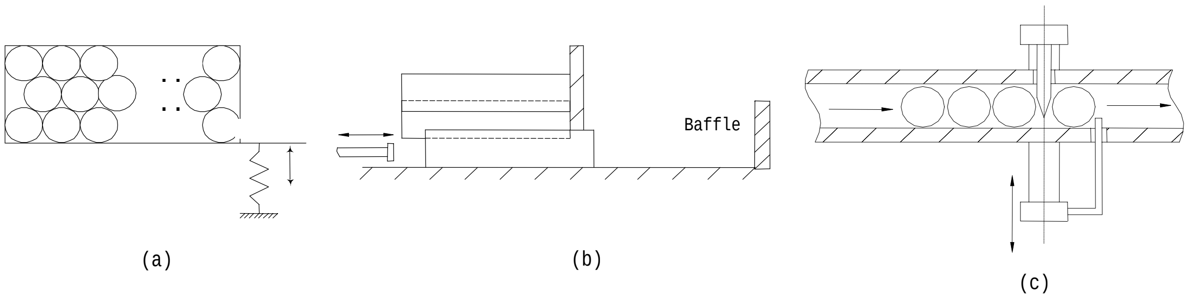

Figure 5. Some design solutions for separating wood sticks

Analyze the state space of the stacks of wood sticks. The possible state changes are as follows: A 3-layer stack can be changed to the sum of a 2-layer stack and a single-layer stack, the 2-layer stack can be further changed to 2 single-layer stacks, and the obtained single-layer stacks can be further changed to separated wood sticks (the desired state). Thus, the wood stick stacks should be separated 3 times, as shown in figure 6(b).

The layer-transformation of the stacks can be achieved by a pushing device, as shown in figure 5(b), which requires the to-and-fro translation (TF translation) as its condition. Because designer can only supply electrical energy, a new function of transforming electrical energy to the TF translation is proposed, which can also be achieved with the combination of an electromagnetism device and a resetting spring. Continue to analyze the unexpected behaviors of the solution. The pushing device on one hand makes the wood stick layers separated; on the other hand, it makes the separated layers with some speed, resulting in the layers deviating from the desired position, which will make the following separating process inconveniently. Therefore, a new function of limiting the movement of layers is advanced, which can be solved by a baffle. The function of changing the wood sticks in the single-layer stacks to separated wood sticks can be achieved by many solutions, in which, the solution shown in figure 5(c) is employed because the separated sticks don't have inertia speed and its conditions are easily satisfied. Figure 6 shows the whole process of generating a separating solution concept in more details. From figure 6, it can be seen that as design proceeds, the functional structure of an artifact evolves from a rough function into the relatively complete functional structure of a desired artifact.

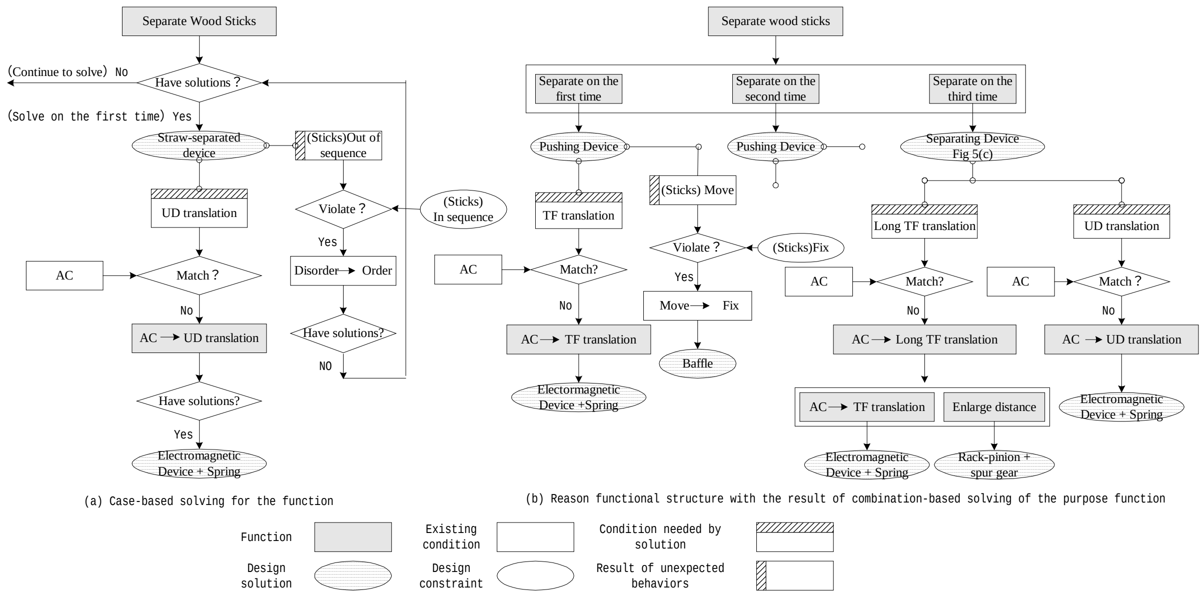

Figure 6. The symbiosis-based functional reasoning process for wood stick-separated machine

6. Conclusion

One of the key issues of computer-aided conceptual design is how to realize computer-aided functional reasoning, which requires a comprehensive understanding of how the functional structure of an artifact comes into being. Enlightened by the symbiosis-based evolution method of organisms, this paper systematically summarizes the symbiotic relations in conceptual design, which are supplying necessary conditions of design solutions, removing the adverse results of unexpected behaviors and smoothing away environmental influences. Based on these relations, a functional structure evolution model is proposed and the conceptual design process of a wood stick-separating device is illustrated to verify the model. The model discloses that the functional structure development process and function-solving process in original design intersect and are carried out concurrently, which is different from that in routine design as Pahl & Beitz proposed. The understanding of the functional structure evolution process, e.g. the functional reasoning process, discloses what knowledge is needed in functional reasoning, which is useful for improving the knowledge representation of design solutions to cater for functional reasoning. In addition, this paper also exposes the influence of unexpected behaviors on functional structure evolution. Therefore, how to predict those unexpected behaviors as early as possible also becomes a critical issue of computer-aided conceptual design. Further researches will be carried out on these issues.

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References

[1] Pahl G. and Beitz W., “Konstruktionslehre”, Springer-Verlag, Berlin, 1986.

[2] Feng P.E., Xu G.R. and Zhang M.J., “Feature modeling based on design catalogues for principle conceptual design”, AI EDAM, Vol.10, 1996, pp.347-354.

[3] Feng P.E., Chen Y., Pan S., et al, “Genetic engineering and conceptual design”, Proceedings of ICED ’01, Vol.3, 2001, pp.235-242.

[4] Feng P.E., Chen Y., et al., “Product gene based conceptual design”, Chinese Journal of Mechanical Engineering, Vol.38, (10), 2002, pp.1-6.

[5] Gero J.S., “Design prototypes: A knowledge representation schema for design”, AI Magazine, Vol.11, (4), 1990, pp.26-36.

[6] Welch R.V. and Dixon J.R., “Guiding conceptual design through behavioral reasoning”, Research in Engineering Design, Vol.6, 1994, pp.169-188.

[7] Chakrabarti A. and Bligh T.P., “An approach to functional synthesis of mechanical design concepts: Theory, applications, and emerging research issues”, AI EDAM, Vol.10, 1996, pp.313-331.

[8] Tian Q.L., Gao C.M., et al., “Biology”, Chemical Engineering Press, Beijing, 1983.

[9] Li N., “Tutorial of Evolutional Theory”, High Education Press, Beijing, 1990.

[10] Li J.W., “Bio-Chemistry”, Peiking University Press, 1993.

[11] Chandrasekaran B., “Design problem solving: a task analysis”, AI Magazine, Vol.11, (4), 1990, pp.59-71.

[12] Goel A.K. and Stroulia E., “Functional device models and model-based diagnosis in adaptive design”, AI EDAM, Vol.10, 1996, pp.355-370.

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