This paper will be included in the Proceedings of Design Theory and Methodology – DTM '95 –, ASME, 1995.

REPRESENTATION OF DESIGN OBJECT BASED ON THE FUNCTIONAL EVOLUTION PROCESS MODEL

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ABSTRACT

One of the crucial issues for developing computer aided conceptual design system is representation of functions which represent *designers' intention.* Representing functions is also crucial not only for representing design objects but also for describing conceptual design processes, in which designers operate mainly functional concepts. Namely, function is a key concept to integrate object modeling and process modeling in design.

In this paper, first we extend the *FBS (Function-Behavior-State) diagram*, which we have already proposed, by introducing three additional concepts for representing a function; namely, *function body* that represents designers' intention directly, *function modifier* that qualifies a function body, and *objective entity* on which the function body occurs. This extended FBS diagram, called *FBS/m (modifier) diagram*, enables us to represent designers' intention more precisely than the original FBS diagram. Then, we propose an *FEP (Functional Evolution Process) model* to represent design processes. In the FEP model, the FBS model of a design object is evolved through three steps, i.e., *functional actualization*, *functional evaluation* and *functional operation.* Functional actualization depicts a process to obtain physical descriptions from functional description. Functional evaluation is a process to measure realizability of functions of the design object. Functional operation is a process to operate functions to improve the design. Based on the FEP model, we analyze some actual design processes, and show that the FEP model is suitable for representing designers' intention along with design processes.

INTRODUCTION

One of the crucial issues for developing computer aided conceptual design system is representation of functions which represent *designers' intention.* Function is a key concept in design, because ideally design produces a design object that fulfills with the required functions (Takeda *et al.,* 1990b). Although function is a well-known concept, its definition is unclear.

The objective of our research is to establish a method for aiding conceptual design and to develop computer aided conceptual design system that realize more natural computer supports in design processes by representing a functional evolution process of design objects. Design is a process in which a representation of a design object which includes functions is gradually refined: this is called *functional evolution.* Recording functional evolution is critical to preserve designers' intentions which is one of the core issues for developing advanced CAD systems and for designing functionally innovative products.

We first discuss properties of function that we want to deal with and roles of function in design. Second, we describe the *FBS (Function-Behavior-State)* modeling (Umeda *et al.,* 1990), and introduce related functional concepts, i.e., *function body*, *objective entity*, and *function modifier*. Third, we propose the *FEP (Functional Evolution Process)* modeling to model a design process in which a model of design object is gradually evolved by applying *functional realization*, *functional evaluation* and *functional operation* iteratively. Finally, we represent some design examples in the FBS and FEP schemes and analyze the results.

ROLES OF FUNCTION

We consider that a function has the following three roles in a design process. Figure 1 depicts the relationships among these three roles.

A. Required specifications
The designer specifies the requirements in terms of functional concepts. Therefore, function should represent designer's intention given as the requirements.

B. Design object representation
Functional concepts describe a design object that can satisfy the requirements. The physical description of the design object should be associated with the functional description.

C. Evaluation
The designer evaluates the design object from the functional view point. Function should be evaluated qualitatively or quantitatively in order to measure how much designer's intention is satisfied.

In order to help designers to conduct design that focuses more on function that has these three roles, we propose two schemes for representing function. One is the *FBS/m* (*m* stands for modifier) *diagram* and the another is the *Functional Evolution Process (FEP) model* that represents how function is operated in the design process.

MODEL OF FUNCTION

In above chapter, we discussed roles of function in design. In this chapter, we propose a model of function for object modeling.

There are many approaches to represent function (e.g., (Roth, 1982) (Pahl and Beitz, 1984)), but there is a common problem that function and behavior are often confused and mixed each other (Ulrich and Seering, 1988) (Iwasaki *et al.,* 1993). For instance, behavior can be defined objectively as transitions of physical states and therefore can be derived

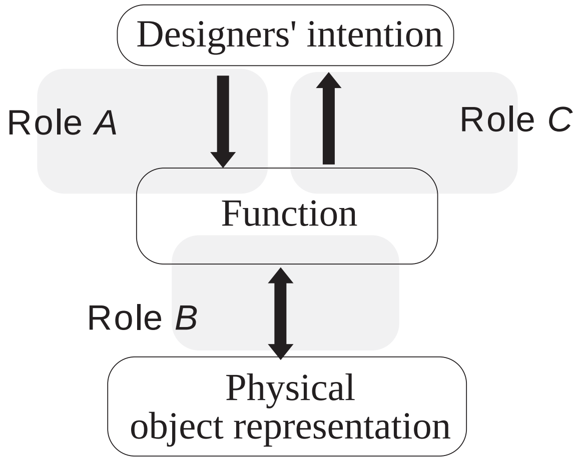

Figure 1: Three Roles of Function in Design

from physical states of an entity and its environment. However, function is related not only to physical behavior but also to the designers' perception of behavior. For example, regarding function of a car, one may say one of its functions is "moving" and others "carrying," even if they observe the same behavior. Therefore, we represent functions based on the FBS diagram in which a function is represented as an association of the designer's intention and a behavior that can actualize this function (Umeda *et al.,* 1990).

However, while the FBS diagram satisfies the role *B* (design object representation), the roles *A* (required specification) and *C* (evaluation) are not fully satisfied. Functional representation in the FBS diagram is limited to the form "to do something," and its evaluation just tells whether or not the function can be performed qualitatively but not the degree of the performance. In this paper, we propose an FBS/m diagram as a representational scheme of function by extending the FBS diagram.

FBS modeling

In the FBS modeling, a state of a design object is represented by entities, attributes of the entities, and relations among entities. While entities are identifiers, attributes of the entities and relations among entities represent their states and structures. Then, a behavior is defined as "sequential changes of states." In the physical world, changes of states are governed by physical laws. We call this set of definitions of state and behavior *view point* that is a basic unit of object representation. A view point consists of definitions of terms (entities, attributes, and relations) and rules (physical laws). A designer has various kinds of view points from

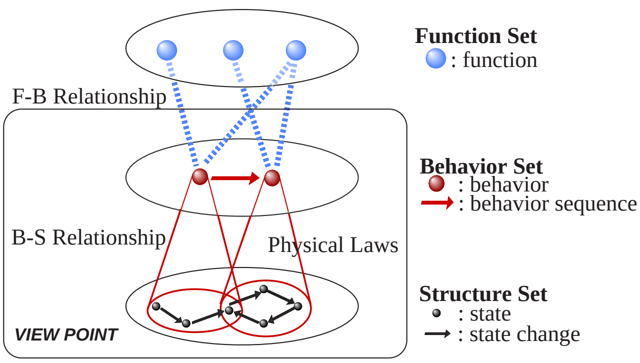

Figure 2: Relationship among Function, Behavior, and State (Umeda *et al.,* 1990)

well-defined ones (e.g., rigid body dynamics) to ill- or vaguely-defined ones (e.g., manufacturability).

We define a function as "a description of behavior abstracted through recognition of behavior for utilization." In other words, while a behavior is an objective concept grounded on states and described within an view point, a function is subjective concept related to behaviors (see Figure 2).

We define structure of function as follows. A function is represented as combination of a *function body*, *objective entities*, and *function modifiers*. A function body is a symbol that carries meaning of the function. A typical function body is a verb word like "to move" or "to carry." We often call a function body to mean a function for short in this paper. An objective entity is an entity that a function occurs on. It should be specified in the state level before the design terminates. A function modifier is a symbol that details the function body. A typical function modifier is an adverb word like "precisely" or "firmly." The difference between a function body and a function modifier in terms of functional evaluation that will be described later is the type of value given by the evaluation. A function body has a relation to its actualizing behavior and is evaluated in a binary manner, that is, a function body is evaluated whether or not it exists in a design object by using the relation. On the other hand, since a modifier includes parametric conditions given by the designer, it is evaluated how much the modifier is achieved in the design object quantitatively.

Relations among functions

Based on the structure of the function, we here introduce four kinds of relations among functions; i.e., *decomposed-into*, *conditioned-by*, *enhanced-by*, and *described-as* relations.

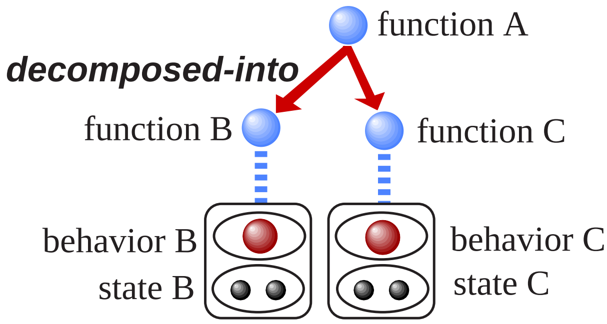

Figure 3: Evolution by Decomposed-into Relation

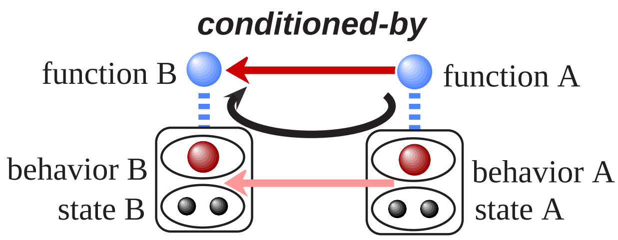

Figure 4: Evolution by Conditioned-by Relation

Decomposed-into relation This relation indicates that a function body is decomposed into sub-function bodies (see Figure 3).

Conditioned-by relation This relation denotes that a new function body B is needed to actualize a function body A. In other words, the function body B is necessary condition for the function body A. This relation should be supported by causal relation in the behavior level (see Figure 4).

Enhanced-by relation This relation denotes that a new function body B is needed for satisfying a modifier $A1$ of function body A (see Figure 5). In this case, though the function body B is not a necessary condition for the function body A, it is assumed that the modifier $A1$ is achieved better by adding the the function body B.

Described-as relation This relation denotes that a modifier is detailed into one or more concrete modifiers (see Figure 6).

FUNCTIONAL EVOLUTION PROCESS (FEP)

As described in above chapter, we clarified functional representation of a design object; that is, functional description is an intentional representation, while behavior and state are objective representation. In this

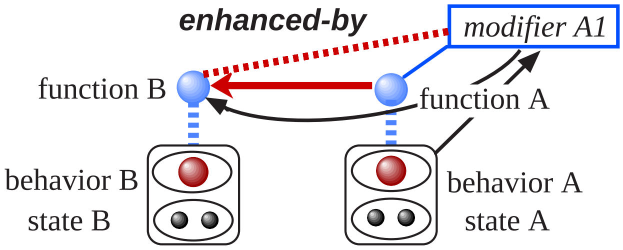

Figure 5: Evolution by Enhanced-by Relation

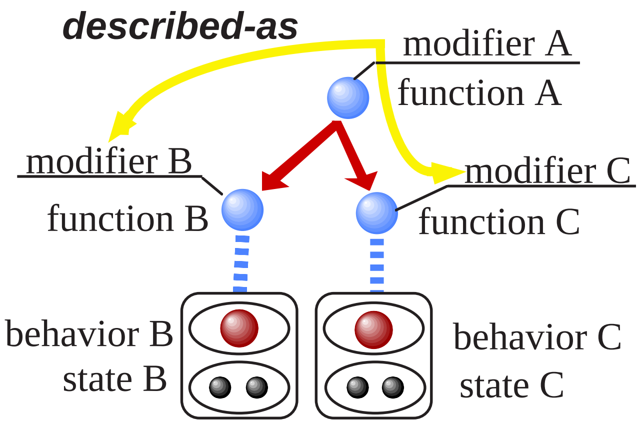

Figure 6: Evolution by Described-as Relation

chapter, we focus on how to operate functions in the design process.

Steps of Functional Evolution Process

One of the three roles of function is to describe required specifications. However, requirements are not complete at the beginning of a design process, and the requirements are also detailed as the object descriptions. In other words, functional descriptions of a design object are gradually refined and detailed as the design proceeds. We call this functional detailing process of a design object a *functional evolution process.*

A step of the functional evolution process is described by functional description, functional actualization, and functional evaluation. Functional description of a design object is revised by the designer at each step of the process. In the FEP (Functional Evolution Process) model, we represent revisions of the functional description with *functional operations.* A functional operation includes operations to modify functional description, i.e., adding new functions, function modifiers, or functional relations. Functional actualization and functional evaluation proposes and justifies adding functions, functional modifiers, or functional relations,

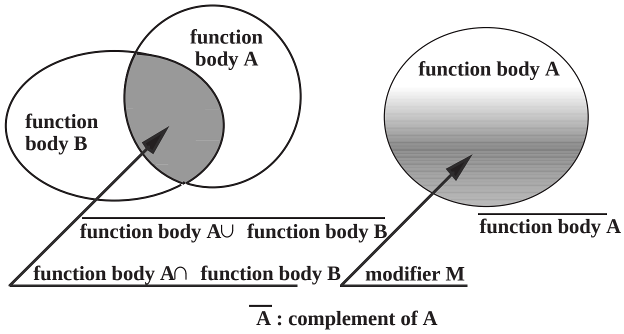

Figure 7: Difference between Function Body and Modifier

respectively.

Functional Description, Functional Actualization, and Functional Evaluation

Functional description is the step in which a designer describes required specifications of the design object with function bodies, objective entities, and function modifiers. Functional actualization corresponds to the step to obtain behavioral description from the functional description by using the knowledge about function. We have proposed a *function prototype* as the knowledge about function for functional actualization (*et al.*, 1993). Functional evaluation means confirming functional description with behavioral description and estimates how intended functions are satisfied by the proposed behavioral description.

As described in above chapter, a function body is evaluated in a binary manner (*et al.*, 1993). However, a designer judges how much a function is achieved in the design object and compares two design candidate solutions with respect to the degree of satisfaction of the specifications. This kind of evaluation is executed for the parametric conditions described in the function modifier of the FBS/m diagram.

However, since this kind of evaluation tends to be subjective, it is not easy to describe the relationship between the parametric conditions and the degree of functional satisfaction. To deal with this kind of subjective relationship, we have proposed *amount of function*, which is defined by probability distribution of subjective evaluation of a physical parameter that characterize function modifiers (Shimomura *et al.*, 1994).

Functional Operation

The main task of a functional evolution process is to obtain a new functional description, which is represented with the functional operations in the FEP model.

We define the following six kinds of functional operations in this model. These six kinds of operations can be classified into two types according to whether or not functional relations are added by each operation. One type includes four kinds of operations each of which generates *decomposed-into*, *conditioned-by*, *enhanced-by*, and *described-as* relations, respectively. The other type includes two kinds of operations that do not generate functional relations; namely, *discovery of functions* and *discovery of modifiers*.

We use the example of the FBS/m diagram shown in Figure 8 for explaining each functional operations. Figure 8 shows a result of an experimental design of a weighting scale obtained by design experiments (Takeda *et al.,* 1990a).

1. Adding functional relations

Decomposed-into operation It is an operation in which a designer decompose a function body into sub-function bodies for detailing it. As a result, a *decomposed-into* relation and some sub-function bodies are added to the FBS/m diagram.

In Figure 8, for example, the function body "to visualize weight" is decomposed into function bodies "to convert weight into displacement" and "to convert displacement and visualize" and a *decomposed-into* relation among these function bodies is also added.

Conditioned-by operation When the designer finds out that an actualizing behavior for function body A is inadequate to occur, this operation is executed to add behaviors necessary for actualizing function body A as follows (see Figure 4):

(a) The designer finds out behavior A associated to the given function body A.

(b) He / she finds out that behavior A will not occur and another behavior B is needed to cause behavior A by using causal simulation (Ishii *et al.,* 1993).

(c) Finally he / she adds a function body B associated to the derived behavior B (see Figure 4) in order to explain why behavior B is attached.

As a result of this operation, a *conditioned-by* relation, a behavior, and a function body for explaining why the original behavior is conditioned by the new behavior are added.

In Figure 8, for example, the designer found out from mental simulation that the function "to translate linear displacement into rotational displacement," of which actualizing structure is "a rack & a spiral gear," is insufficient. Therefore, the designer added another actualizing structure "a lever" to use "the rack & the spiral gear" effectively. This behavior is then recognized as a function "to translate spring displacement into linear displacement" by the designer.

Enhanced-by operation When the designer finds out that a modifier is not actualized enough, e.g., by executing the functional evaluation, this operation is executed. This operation generates an *enhanced-by* relation, a function body related by this relation, and a behavior actualizing the generated function body (see Figure 5).

This operation is typically executed as a result of functional evaluation. When a behavior is proposed to actualize the function A, the designer can evaluate this behavior using a functional modifier $A1$ attached to function A. Namely, functional modifier $A1$ is used for showing how much function A is satisfied with the proposed behavior to the function A. Then the designer would add another function B in order to increase the value of the function A. In other words, this new function B realizes functional modifier $A1$.

In Figure 8, a function "to enumerate rotation" is actualized by the "rotation plate." The designer examines whether or not the rotation plate can actualize the function with the functional modifier "as large as possible." Then the designer finds out that another function "to enlarge an indicator" is needed to achieve the functional modifier adequately. The evaluation of the functional modifier is essential to encourage the designer to find out additional functions in this type.

Described-as operation After a *decomposed-into* operation, this operation is typically executed in order to detail a functional modifier into one or more concrete functional modifiers. When a function body with functional modifiers is decomposed into some function bodies, these sub-function bodies cannot be evaluated precisely without functional modifiers; so, the designer interprets the modifier for the super-function body into those of the sub-function bodies. As a result of this operation, a *described-as* relation and some functional modifiers for sub-function bodies are added (see Figure 6).

In Figure 8, for example, the functional

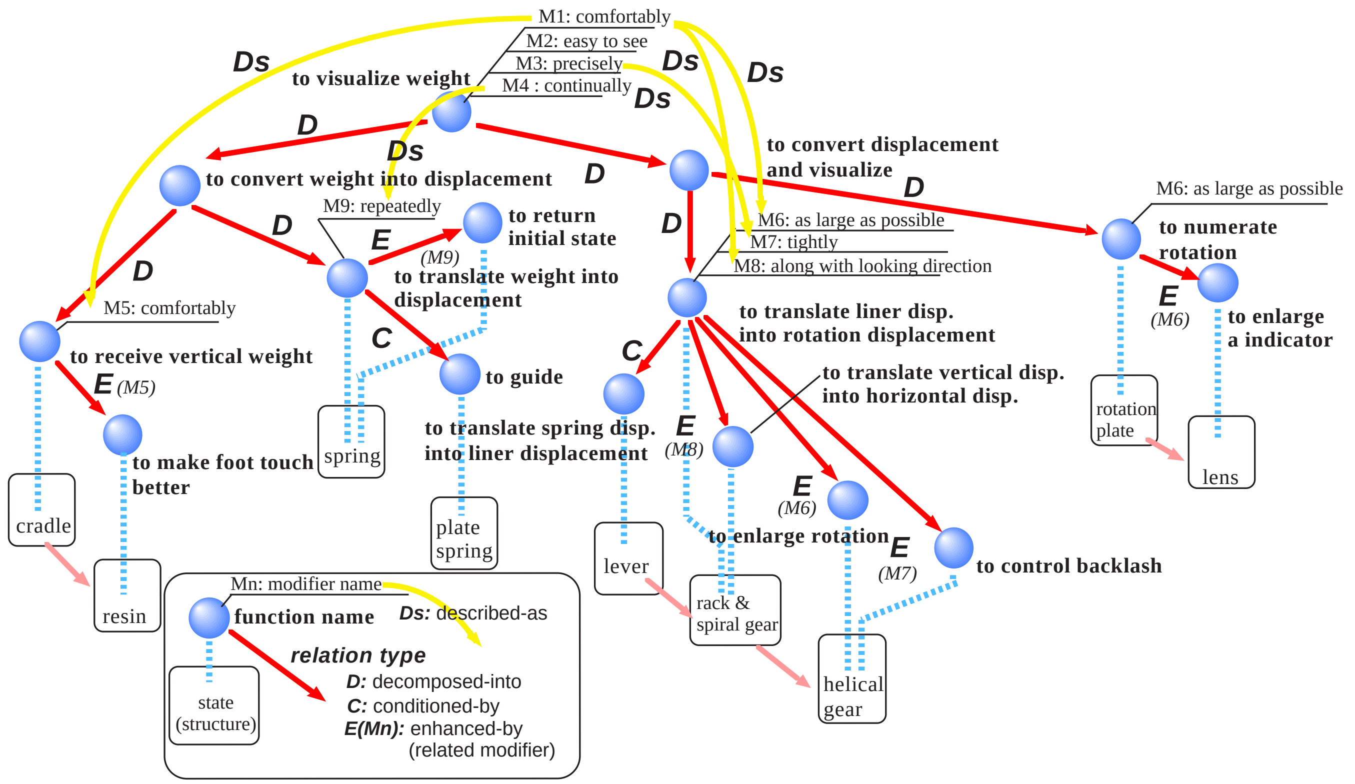

Figure 8: Functional Evolution in Design of a Weighting Scale

modifier "comfortably (M1)" of the function "to visualize weight" is detailed into three functional modifiers; namely, "comfortably (M5)" of the function "to receive vertical weight," and "as large as possible (M6)" and "along with looking direction (M8)" of the function "to translate linear displacement into rotation displacement." Each of which is considered as a more concrete functional modifier than "comfortably (M1)."

2. Discovery of functions and modifiers

Discovery of functions The designer finds out new functions from existing behavioral descriptions. First, the designer proposes a new behavior as actualization of the given function. Then, functional evaluation may show functions other than the designer noticed, because the designer specifies only those necessary functions. These functions can be included in the functional description if they are desirable.

Discovery of modifiers The designer also finds out new modifiers from existing behavioral descriptions. When it is found that a newly proposed behavioral description may have advantages or disadvantages compared with the prior description by executing functional evaluation, the designer adds modifiers to the FBS/m diagram in order to describe these advantages or disadvantages if the designer considers useful.

ANALYSIS OF AN ACTUAL DESIGN PROCESS

In this chapter, we analyze an actual design process of a photocopier using the FBS and FEP schemes.

Modeling Method

First, we collected the documents and the technical drawings about a photocopier and interviewed with the designers to complement these documents. Then, we extracted FBS elements, namely, functions, function modifiers, behaviors, and states according to the following criteria.

Function Body and Objective Entity We regarded verbs that explain the design object as

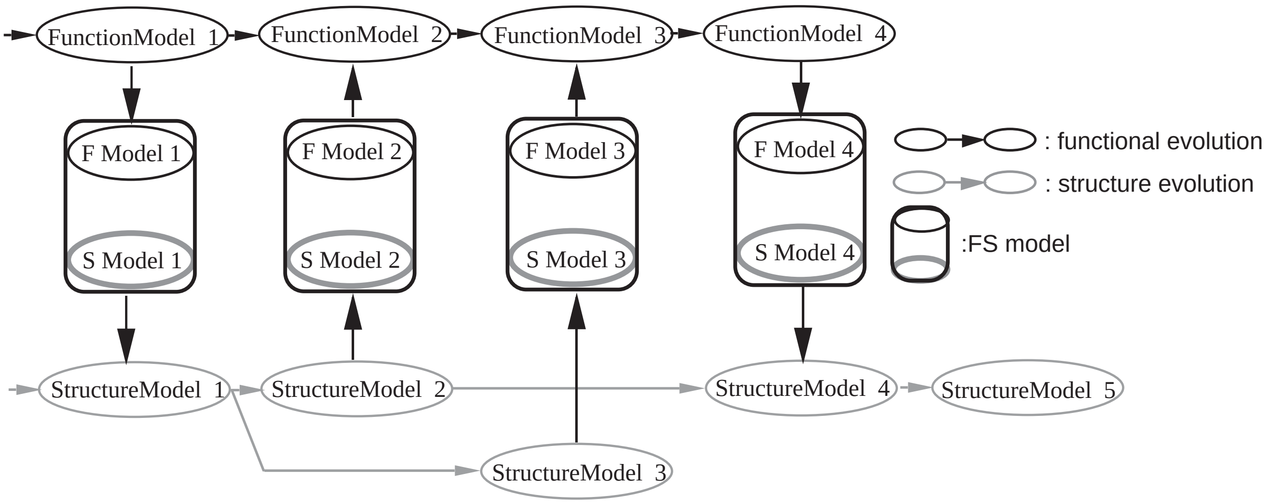

Figure 9: Combination of Function and Structure Models

function bodies. We picked up verbs as function bodies and objective words as objective entities.

Function Modifier We interpreted adverbial phrases as function modifiers. Here, we also interpreted explanations of functions (e.g., "along with looking direction" in Figure 8) as functional modifiers.

Behavior and States Behavior is appeared when the designers invoke simulations. The problem is that such simulation is often executed manually with non-verbal actions. For example, the designers simulate motion by operating physical objects, with drawings or even mentally. However, because in this design example the designers explained the photocopier in terms of structure, we focused on only the structure instead of behavior and state of the photocopier. We traced revisions of the structural descriptions along the design process by observing their drawings and interviewing with them, and represented the structure instead of behaviors used in it. Here, we represented the structures symbolically by using entities, relations among entities, and attribute of entities.

After extraction of the FBS elements, we constructed descriptions of the FBS model at each step of the design process, which we call *FS models*. An FS(Function-Structure) model consists of three elements that are function, structure, and functional relations. We represent the FEP model of this design process by tracing the evolution of the FS models.

First, we modeled functions and function modifiers at each step of the design process, in which functions or function modifiers were added newly or changed, and then ordered the function models linearly according to the actual design process.

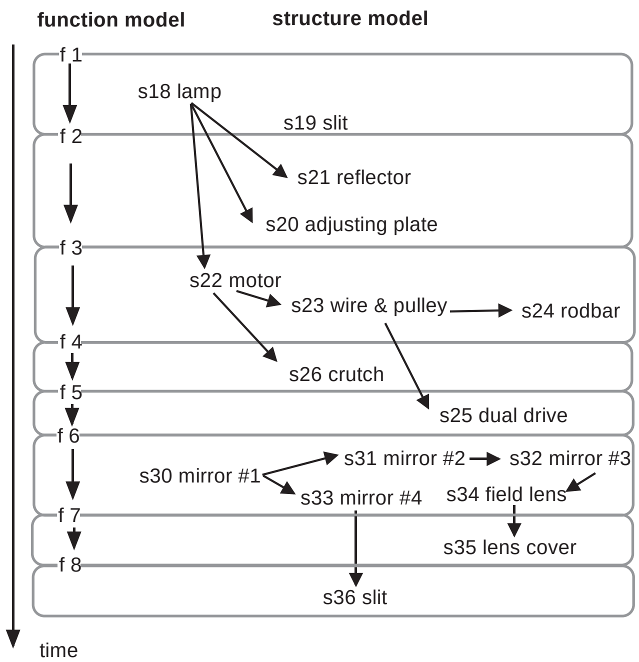

Figure 10: Example of Evolution of FS Models

Second, we focused on the structures that the designers proposed in design. We modeled structures at each step of the design process, in which structures were added newly or changed, and then ordered the structure models linearly according to the actual design process. A structure model was partially based on the earlier structure models.

Finally, we could build an FS model at each step by combining the function model and the structure model (see Figure 9). Figure 10 depicts the FS model of the photocopier. Figure 11 shows examples of relations among functions and structures as an FS model. In figure 10, a symbol starting with f indicates a function model, a symbol starting with s indicates a structure model and its short explanation. An arrow indicates a relation between structure models.

Analysis of the functional operations

In this chapter, we investigate how each function or functional modifier was developed in the design process. Table 1 shows the numbers of appearance of functional operation types.

Decomposed-into operation It has been claimed that decomposition of functions is the most basic procedure to deal with functions in design (Pahl and Beitz, 1984). In this design, we found 53 decomposed functions in this category.

Conditioned-by operation This is the procedure to add functions needed to cause the existing functions. Since most of behaviors are implicit or nonverbal, it is difficult to find such causal relations. However by interviewing the designers, we found 10 functions in this category.

Enhanced-with operation In our model, converting modifiers into functions is achieved by adding *enhanced-by* relations. An enhanced function is found by evaluating the modifiers. The initial function model of this design had relatively a few functions and many modifiers. It implies that interpretation of those modifiers plays important role in this design. In this design, we found 29 functions in this category.

Described-as operation A typical procedure observed in this design process is adding modifiers with *described-as* relations. This way to add modifiers gives more detail descriptions to other modifiers. In this design, we found 30 modifiers in this category.

Discovery of functions A new function is added by examining a newly suggested structure model. It is similar to decomposing functions, but added functions are auxiliary or unexpected functions so that they are not relevant to the existing functions. New functions are found either by positive reasons or by negative reasons. The former means that the proposed structure can satisfy an unexpected function, and the latter means that the proposed structure cannot satisfy an unexpected function. In both cases, a newly found function itself is added to the function model. Unless the structures used in this design is well investigated or well known to the designers, it was not easy to discover this type of functional operation. Therefore, in this design, we could not find any functions in this category.

Discovery of modifiers Figure 12 illustrates how discovery of modifiers is executed. First, a function model and a structure model are provided as the current model of the design object (see Figure 12(a)). After executing functional evaluation by comparing the function model with the structure model, the designers suggest a new structure model in order to realize the function model (see Figure 12(b)). Then, behavioral simulation is executed for this structure model, and a function model for this structure model is created by functional operations (see Figure 12(c)). If the new function model is considered better than the previous one, the new modifiers representing the difference are added to the functional description of the design object. If the new function model is considered worse, negation of the modifiers representing the difference is added by the designers (see Figure 12(d)).

It is interesting that adding modifiers for negative reasons appeared more frequently than ones for positive reasons. It suggests that contradiction of function model and structure model is important to drive design (we have already discussed inconsistency in design process and modeled use of inconsistency in design (Takeda *et al.,* 1992)). In this design, we found 9 modifiers in this category.

As we mentioned, there are relatively a few functions and many modifiers in the initial function model of this design. It means that operating modifiers is important process to evolve function models.

CONCLUSION

In this paper, we discussed properties and roles of function in design and proposed a representational scheme of function which includes function bodies, objective entities, and function modifiers. Furthermore we proposed the FEP (Functional-Evolution-Process) model in which a design object is gradually evolved according to results of functional evaluation, and 6 types of functional operation were defined in the FEP model. Finally we analyzed an actual design process based on the FEP model. We can draw some remarks from this analysis.

1. **Recording revisions of functions is indispensable to trace design processes.**

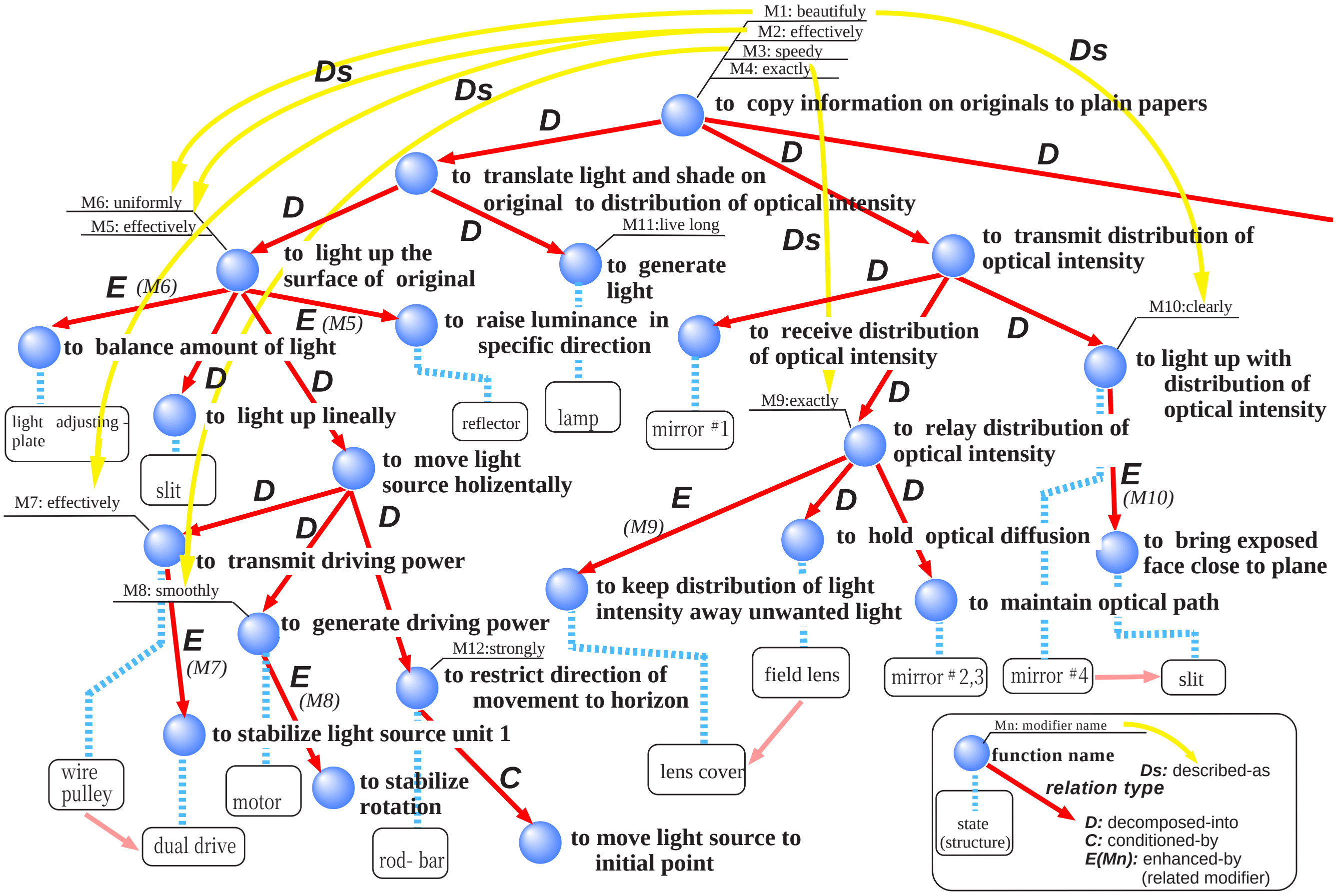

Figure 11: An FS model of the Photocopier Design (Optical Part)

Existing research effort mainly focused on revisions of structures to clarify what happened in design processes. However, recording functional descriptions is also necessary to clarify the designers' intention, and the FS model described in the analysis is appropriate for this purpose, because revisions of functions and structures are represented explicitly in this model.

2. **Function models are also results of design.** Not only the designed structure but also its functions the designers intended are results of design. Here, the functions of a design object include not only the requirements given by the designer at the beginning of the design process but also functions added by the functional operations and discoveries during the design process.

3. **Functional evolution is not magic but rational in most cases.** Designers often determine their own design criteria in order to converge their design processes. Designers seem to have such criteria a priori, and such criteria, which are represented as function modifiers, are detailed more concretely by the designer as a result of the functional evaluation in the FEP model. One of the advantages of the FEP model is that the reason the designer adds new functions and modifiers is described explicitly.

Future works includes:

- Applying the FBS and FEP schemes to actual design of photocopier by collaborating actual designers.
- Developing computer aided conceptual design system that can realize more natural computer supports in design processes and support designers to execute innovative design.

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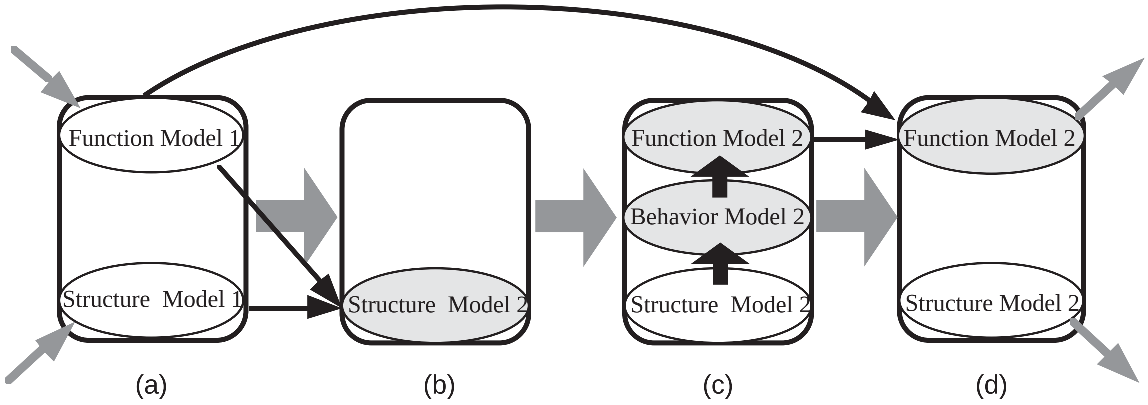

Figure 12: The Process of Discovery of Modifiers

Table 1: Numbers of Appearance of Evolutional Steps

Discovery of functions		0	
	by positive reasons		0
	by negative reasons		0
	by other reasons		0
Functions with *be-decomposed-into* relation		53	
Functins with *be-conditioned-by* relations		10	
Functions with *be-enhanced-by* relations		29	
Discovery of modifiers		9	
	by positive reasons		2
	by negative reasons		6
	by other reasons		1
Modifiers with *be-described-as* relations		30	
Total		131	

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