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VERIFICATION OF A MODEL OF SYNTHESIS - THE METHODS FOR VERIFICATION AND RESULTS

Akira Tsumaya, Yutaka Nomaguchi, Masaharu Yoshioka,
Hideaki Takeda, Tamotsu Murakami, and Tetsuo Tomiyama

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1 Introduction

Engineering design consists of a variety of thought processes, but most of them can be classified into two types, analysis and synthesis. There is a need to build an advanced CAD system that can support not only analysis but also synthesis. However, traditionally, CAD technologies have paid little attention to synthesis. Our project team, "Modeling of Synthesis", has focused on the synthesis thought process [1] and proposed a thought process model based on knowledge level operations [2][3]. Following these results, this paper reports the verification phase of the project.

We verify the knowledge operation model with the following two methods. One is to test the model against experimental data, and the other is to implement a system based on the model to examine if the system behaves in accordance with the designers' behavior. In this paper, we use the former method and evaluate the applicability of the model by comparing it with other existing design process theories.

In this paper, first, we explain how to select a design case for verification. Second, we propose a method to build a reference model of the design case. This reference model is framed in the knowledge operation model and other existing design process theories, viz., the cognitive design process model of Takeda *et al*. [4] and German design methodology of Pahl and Beitz [5]. By doing so, we can compare the knowledge operation model with these existing theories. From this comparison, we can evaluate and verify the knowledge operation model.

2 Selection of a design case for verification

Before verification, we need to set up a method to select a design case. Observing and recording an actual industrial design case is difficult because of proprietary reasons and data amount. Protocol analysis of design experiments such as Delft design protocol [6], provides us with detailed data, but this approach often became a toy case, because of the limitation of resources and laborious work for analysis.

For the verification of a design process model including synthesis process, design cases are required to satisfy the following conditions:

- The design cases should be real design cases, but they should not be toy problems nor created cases for verification.

- The design cases must have “newness” which is the most important essence of synthesis.

- Concrete data about the design process should be recorded.

- The data of the design cases should be of a reasonable size for analysis. They should not be too huge or complicated.

Considering these conditions, we selected a machine design conducted in a laboratory at the University of Tokyo over four years. The design was the development of a high precision stereo lithography machine for micro photoforming fabrication of micro flexible mechanisms [7]. This research contains “newness” that tries to increase manufacturing accuracy, and the amount and size of the data are reasonable. As the sources of information, we used three bachelor theses completed in 1995, 1996, and 1997, a PhD thesis in 1998, summary reports of the research written occasionally, and weekly reports that usually consist of several lines about what the student did in a week. We investigated these sources to analyze design activities.

From this design case, we built a “reference model” of design process for verification of the model of synthesis.

3 The method to build a reference model

3.1 Building a reference model using design activities

After selecting the design case, we built a reference model. To do so, we introduced the concept of the frame cognition model that classifies design activities into some categories, viz., “naming”, “framing”, “moving” and “reflecting” [8]. Figure 1 shows the relationships among them. The subject that relates to the present design conditions is posed by “naming”. The “framing” builds up a problem in a frame. The design proceeds to a solution categorized to “moving”. The solution is evaluated by “reflecting”. Design protocols are analyzed and categorized into these four activities. Using this classification, the design case was analyzed into sequentially framed design processes and a reference model was obtained.

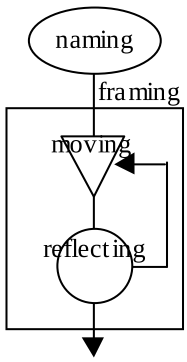

Figure 1. Design Activities of the Frame Cognition Model [8].

The frame cognition model had some problems as well, because this model was originally proposed as a result of the protocol analysis of the conceptual design of a simple component

[6]. Therefore, we had to modify the frame structure to accommodate our design case that was more complicated than the original design experiment. We needed to have, first, hierarchical structure of design processes and, second, consideration about information flow through design activities. Adding these two modifications, design activities were picked out from the sources of the design case, and arranged sequentially. Figure 2 illustrates a part of the reference model displayed in the frame cognition model.

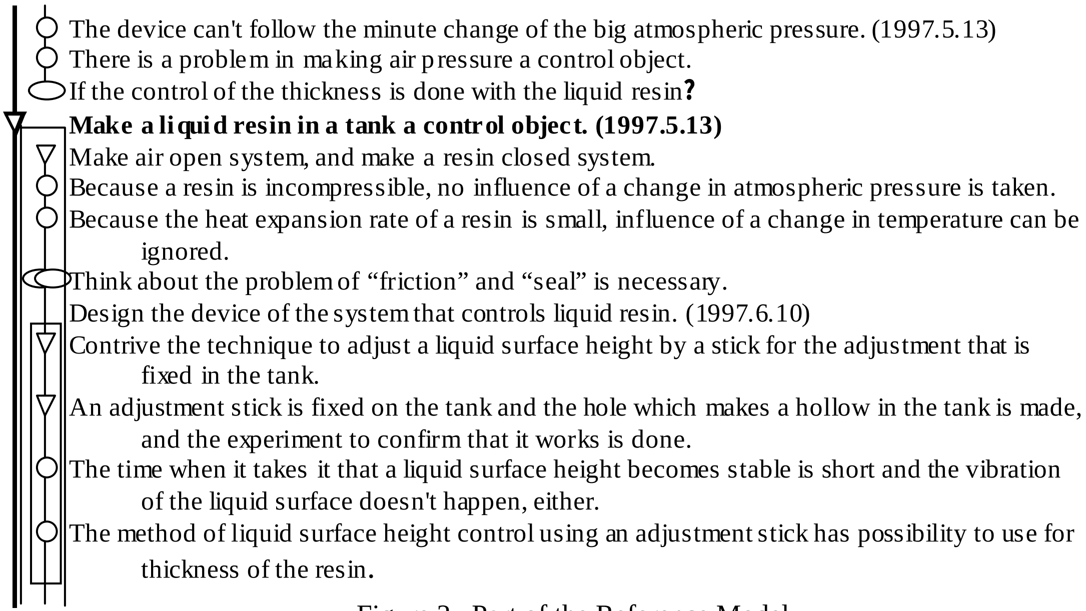

Figure 2. Part of the Reference Model.

Then, we began to verify our proposed design thought process model based on knowledge operations (for further details, interested readers might refer to [2] and [3]). This model, called the knowledge operation model, contains seven knowledge operations: "knowledge/information acquisition", "knowledge/information reorganization", "information confirmation", "conflict resolution", "knowledge/information revision", "solution synthesis", and "object analysis". For the verification of completeness of the knowledge operation model, we checked the correspondence of the seven knowledge operations with design activities in the reference model. Consequently, we could confirm that the seven knowledge operations cover the reference model. Roughly speaking, three knowledge operations, "solution synthesis", object analysis", and "conflict resolution", are cycling in this order. "Information confirmation" is usually observed when the focus of design changes from one component to another, from the whole design object to components, and from a component design to the whole. Another three knowledge operations appear randomly.

3.2 Using vocabulary about design

To evaluate the applicability of the knowledge operation model, we compared it that represents the reference model with other design process models (such as [4] and [5], see Section 4). This resulted in some problems, however, and the biggest problem was that one design activity in the reference model sometimes corresponded to more than one stage of these design process models. This happened due to the difference in the concept granular sizes between a design activity and a stage of the design process models. Because of this, we introduced an intermediate abstract level between them, called *design vocabulary* and composed of standardized terms about design to represent each design activity at more general and detailed level.

For example, we show the following design activities from the reference model.

- "*Because of the moving mechanism of the table at the top, the upper contact side of the tank deviates and a hollow warps caused by the movement of the table.*"

- "*Should I fix a table (X-Y table) at the top of the tank?*"

- "*The X-Y table is relocated to the bottom of the tank, and the top of the tank is unified with the tank.*"

This series of design activities can be interpreted with the design vocabulary as follows.

- The "estimation" of "*Because of the moving mechanism* …" and "knowledge acquisition" were performed due to the contradiction in the experiment, and information is collected by the "investigation" to solve the problem.

- The "idea" of "*Should I fix* …" appeared in the process of the "arrangement of the information" of the collected information.

- According to the idea, "knowledge acquisition" and "knowledge reorganization" are carried out, and then "suggestion" of "*The X-Y table is changed…*" is made.

Using this interpretation, the three design activities in the example above are represented more precisely and uniformly by eight terms. In the same way, each design activity can be explained with the design vocabulary. The vocabulary included 112 standard terms that were obtained through brainstorming of all members of the project. All design activities in the reference model were interpreted, and consequently, 102 design activities were converted into 223 terms correlated to 23 categories of the design vocabulary. We also analyzed the correspondences between the knowledge operation model and the design vocabulary. As a result, we found out that each term in the design vocabulary is correlated to only one of the knowledge level operations. Table 1 shows the result of the analysis.

Table 1. The results of the analysis by using vocabulary about design.

Stage of the knowledge level operation (times of appearance)	**Vocabulary about design (times of appearance)**
Knowledge/information acquisition (61)	investigation (26), knowledge/information acquisition (19), problem indication (16)
Knowledge/information reorganization (33)	arrangement of the knowledge/information (13), knowledge/information reorganization (10), making concrete (7), drafting (3)
Information confirmation (10)	confirmation (10)
Conflict resolution (8)	conflict resolution (8)
Knowledge/information revision (9)	strengthening of the constraint (6), knowledge/information revision (3)
Solution synthesis (44)	suggestion (24), idea (8), selection (7), improvement (3), decision (1), association (1)
Object analysis (58)	evaluation (27), trial manufacture (14), experiment (9), estimation (4), numerical analysis (3), derivation (1)

4 Comparison of the knowledge operation model with existing design theories

In this section, we verify the knowledge operation model by comparing the model with other existing design theories. The method for comparison between the knowledge operation model and the existing design process theories is shown as follows.

1. Analyze the knowledge operation model that frames the reference model with the design vocabulary, and check the correspondences of the knowledge operations and the terms in the design vocabulary.
2. In the same way, analyze and check correlation between stages of an existing design process theory and terms that represent the reference model.
3. Obtain the relationship among the design process models using the terms in the reference model as a mediator.

4.1 Comparison with the cognitive design process model

First, we compared the knowledge operation model with the cognitive design process model of Takeda *et al.* [4] using the reference model as a mediator. The cognitive design model has the following five sub-processes, viz., "*awareness of the problem*", "*suggestion of candidate solution*", "*development*", "*evaluation*", and "*decision*". Table 2 illustrates the comparison result between the two models that shows good correspondences between them. For instance, "*Suggestion of candidate solution*" corresponds to "**solution synthesis**", "*Development*" to "**object analysis**", and "*Evaluation*" to "**object analysis**". "*Decision*" corresponds to "**information confirmation**" and "**conflict resolution**". In the former, the designer made positive judgment to a solution whereas the designer found some problems about a solution in the latter. "*Awareness of the problem*" corresponds to "**knowledge/information acquisition**", "**knowledge/information reorganization**", and "**knowledge/information revision**", but often implicitly.

We also found that the cognitive design process model cannot classify some terms of the knowledge operation model. This is because the cognitive model treats nothing about information from outside, whereas the knowledge operation model has consideration about that.

4.2 Comparison with German design methodology

In German design methodology (e.g., [5]), the designer begins design with analysis and decomposition of functional requirements, followed by embodiment of function into structure. Because our design case is conceptual, we focused on two parts of the design process in German design methodology, viz., "clarification of the task" and "conceptual design". "Clarification of the task" contains two stages, i.e., "*clarify the task*" and "*elaborate the specification*". "Conceptual design" consists of "*identify essential problems*", "*establish function structure*", "*search for solution principles*", "*combine solution principle and select suitable combination*", "*firm up into concept variants*", and "*evaluate against technical and economic data*".

Next, we compared the knowledge operation model with German design methodology. Table 3 exhibits the result of the comparison, "*Identify essential problems*" corresponds to "**knowledge/information acquisition**", and "*Establish function structure*" to “**knowledge/information reorganization**”. “*Search for solution principles*” and “*combine solution principles and select suitable combinations*” correspond to “**solution synthesis**”. “*Firm up into concept variants*” corresponds to “**object analysis**”. “*Evaluate against technical and economic criteria*” corresponds to “**object analysis**”, “**information confirmation**”, and “**conflict resolution**”. In this stage, first, “evaluation” of a design solution is performed, followed by “confirmation” or “conflict resolution”. “*Clarify the task*” corresponds to “**knowledge/information acquisition**”, and “*elaborate the specification*” to “**knowledge/information revision**”. These two mainly follow “conflict resolution”. This result shows similarity of the two models. However, our proposed model has advantage to interpret functional design in that our model can not only acquire and refer to functional information but also treat other types of information, such as physical entities which traditional functional decomposition method cannot handle.

Table 2. Comparison the knowledge level operation model with the cognitive design process model.

		awareness of the problem	suggestion	development	evaluation	decision	cannot be classified
knowledge / information acquisition	investigation						26
	knowledge/information acquisition						19
	problem indication	16					
knowledge / information reorganization	arrangement of the knowledge/information						13
	knowledge/information reorganization	2					8
	making concrete	7					
	drafting						3
information confirmation	confirmation					10	
conflict resolution	conflict resolution					8	
knowledge / information revision	strengthening of the constraint	6					
	knowledge/information revision	3					
solution synthesis	suggestion		24				
	idea		8				
	selection		7				
	improvement		3				
	decision					1	
	association		1				
object analysis	evaluation				27		
	trial manufacture			14			
	experiment			9			
	estimation			4			
	numerical analysis			3			
	derivation			1			

Table 3. Comparison the knowledge level operation model with German design methodology.

		clarify the task	elaborate the specification	identify essential problems	establish function structures	search for solution principles	combine solution principle and select suitable combination	firm up into concept variants	evaluate against technical and economic criteria	cannot be classified
knowledge / information acquisition	investigation			26						
	knowledge / information acquisition	1		5						13
	problem indication	16								
knowledge / information re-organization	arrangement of the knowledge / information				13					
	knowledge / information reorganization				9					1
	making concrete				7					
	drafting									3
information confirmation	confirmation								7	3
conflict resolution	conflict resolution								8	
knowledge / information revision	strengthening of the constraint		6							
	knowledge / information revision		3							
solution synthesis	suggestion					24				
	idea					8				
	selection						7			
	improvement					3				
	decision						1			
	association					1				
object analysis	evaluation								27	
	trial manufacture							14		
	experiment							9		
	estimation								4	
	numerical analysis							3		
	derivation							1		

5 Conclusions

We proposed a new method, called a reference model, to verify the knowledge operation model of synthesis. To do so, we investigated how to select a suitable design case. A reference model was built from an actual design case and design activities were identified. Furthermore, we introduced abstract standard terms, called design vocabulary, to build a reference model. By using the reference model described with the design vocabulary, we confirmed that the knowledge operation model could cover the reference model with good correspondence. This justifies the completeness of the knowledge operation model. We also compared it with other design process theories and found that the knowledge operation model is compatible with them.

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TSUMAYA, Akira
Collaborative Research Center for Advanced Science and Technology, Osaka University, Yamadaoka 2-1, Suita, Osaka 565-0871, Japan, +81-6-6879-4191, +81-6-6879-4191, tsumaya@crcast.osaka-u.ac.jp, http://www.crcast.osaka-u.ac.jp/crcast23/index-e.html