INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

ORGANIZING KNOWLEDGE ABOUT FUNCTIONAL DECOMPOSITION

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Abstract

Although importance of knowledge sharing among designers has been widely recognized, the knowledge about functionality in the conceptual design phase is often scattered across technical domains and it lacks consistency. Aiming at capturing such functional knowledge consistently to make it applicable to other domains, we have developed a framework for its systematic description based on the ontologies of functionality. This paper discusses a functional-knowledge modeling process based on two types of functional models, two types of organizations of knowledge, and two ontologies. The concept of “way of function achievement” plays a crucial role in distinguishing the knowledge about functional decomposition from functionality itself and organizing the knowledge. A successful deployment of our framework in a production company is also discussed.

Keywords: knowledge modeling, knowledge sharing, functionality, ontology

1. Introduction

Functionality plays a crucial role in the conceptual design of engineering devices [1,2,3,4,5,6]. For example, a designer often decomposes a required function into sub(micro)-functions, so-called functional decomposition [1]. As a result, a designer obtains a micro-macro hierarchy of functions, which represents how the required (macro-)function is achieved by sub(micro)-functions, as a conceptual skeleton of the product realizing the requirement. Because there are many methods to achieve a specific function in general, designers should select an appropriate one from many alternatives. Such an activity requires knowledge of how to achieve a function, which represents possible patterns of achievement relations among functions.

However, it is difficult to describe such a functional knowledge consistently and share the functional models and generic knowledge about functionality in spite of that the advancement of computer technologies has enabled easy access to structural information on CAD. General knowledge so-called “design catalog” also mainly focuses on mechanism concerning shape and link. Although many functional modeling languages have been proposed (e.g., [3,4,7,8]) there is neither rich common vocabulary for representing functions nor well-established ontological commitment for capturing such knowledge. For the former issue, only a few (4-16) generic functions have been proposed to date [1,2,7]. Although a set of 158 verbs representing function has been proposed in Value Engineering area [9], it is only for human comprehension. For the latter issue, for example, one might describe “to weld objects” as a function of a manufacturing facility in the similar manner in value analysis [10]. However, “to weld” is not only a function but also implies a certain way to achieve the goal, the objects are fused. In fact, the same goal can be achieved in different ways (e.g., using bolts and nuts) without fusion. To allow freedom in design and to make selection of “bolt & nut” instead of “welding” possible, the achieved function should be the same; “to join”. This example suggests necessity of carefully designed vocabulary of functions and an ontological framework for functions beyond just lexical vocabulary.

The main goal of this research is to promote sharing of the functional design knowledge among human designers by providing a framework for systematic description of the functional knowledge based on Ontological Engineering. Ontologies can provide fundamental concepts for capturing the target world in a consistent way and they can provide a vocabulary for description of knowledge. Such concepts help us improve consistency and generality of knowledge. We have developed two ontologies for functional knowledge, namely, an extended device ontology and a functional concept ontology [11,12].

This paper discusses ontology-based systematic modeling of functionality of products and functional knowledge. Firstly, we overview our modeling framework in which six types of knowledge. The modeling process consists of modeling of concrete products and organizing of generic knowledge extracted from the concrete models. The key issues in the former instance modeling step are to capture the "way of function achievement" and to use the functional concept ontology as discussed in Section 3. In the knowledge organization step discussed in Section 4, independence of viewpoint is important. Section 5 presents usages of our framework and a successful deployment of our framework in a production company and we analyze the success factors. Section 6 discusses related work, limitations and application domains of our ontologies, and further issues in our collaborative research with the ICA group of Delft University of Technology. Lastly, Section 7 gives concluding remarks.

2. Overview of a framework for functional-knowledge modeling

We define a "function" of a device as a conceptualization of result of teleological interpretation of its "behavior" under the intended goal [13]. The "behavior" is defined as objective (without designer's intention) input-output relation of the device as a black box based on a device-centered ontology [12]. A device is connected to another device through its input or output ports. A device as an agent changes states of things input (called *operands*) such as substance like fluid, energy, motion, force and information. The input-output relation of the behavior is, to be exact, the difference between the states of the operand at the input port and that at the output port. A device can be a mechanical element, a mechanical pair, a component, an assembly, a sub-system, and a system. Those include both products and manufacturing machines. Teleological interpretations of manufacturing activities are also regards as functions. We consider verbs representing functions to be *functional concepts*.

Our definition of behavior and function is similar to those in [4,7,14,15] in a sense of intention. However, we explicate mapping primitives between behavior and function (called functional toppings [13]) and operational conceptualization of the functional concepts. On the other hand, papers such as [3] define that "behavior" is how to achieve a function.

Our framework for functional-knowledge modeling is shown in Figure 1. This framework is an extension of our functional modeling language FBRL (abbreviation of a Function and Behavior Representation Language) [13]. It shows a modeling process from a functional model of a concrete artifact to organized generic knowledge. It includes six kinds of knowledge about functionality. Firstly, a *function decomposition tree* (Figure 1(a) and Figure 5) models a functional structure of a specific device. It basically represents that a required function (called a macro-function) can be achieved by specific sub(micro)-functions [1]. All functions (rounded box nodes in the tree) in the functional decomposition tree are instances of generic functions defined in the *functional concept ontology* (e) [11] based on *an extended device ontology* (f) [12]. We introduce the concept of "way of function achievement" as

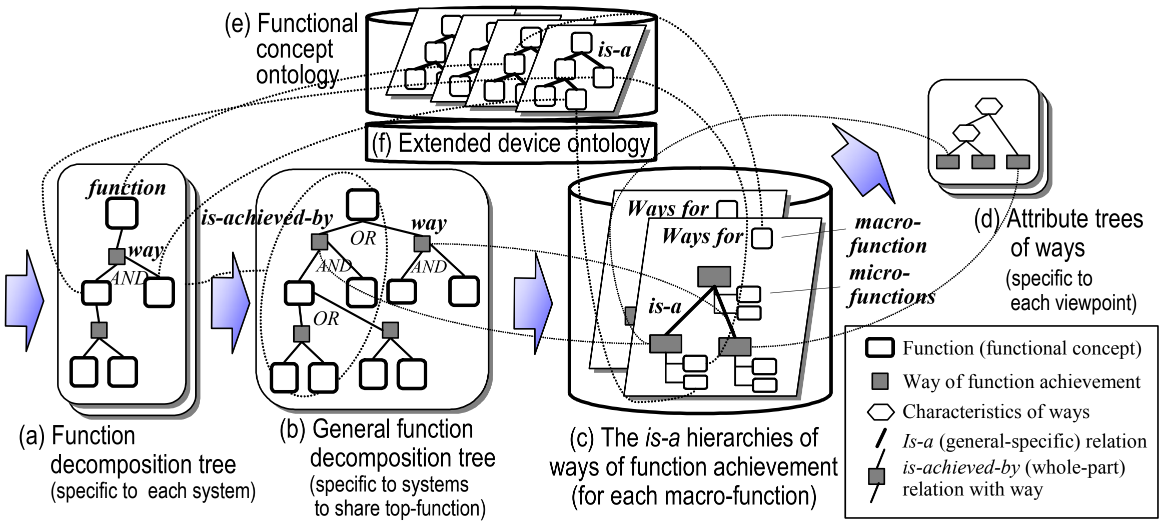


Figure 1. A process of functional-knowledge modeling.

conceptualization of "how to achieve a function" as discussed later. In the functional decomposition tree, a way of function achievement is denoted by a gray box node that connects the macro-function and the micro-functions.

Secondly, a *general function decomposition tree* (b) is composed of some function decomposition trees of similar devices having the same whole-function. It includes alternative ways of function achievement in OR relationship. It represents possible ways to achieve a specific function. This step can be omitted. These two steps will be discussed in Section 3.

Lastly, a concrete way in a (general) function decomposition tree is generalized into a generic way (called functional way knowledge). Then, ways to achieve the same function is organized in *is-a* relations according to their principles (called an *is-a hierarchy of ways of function achievement* (c) and Figure 3(a)). We distinguish the organization as an *is-a* hierarchy from the other derivative organizations depending on viewpoints (called an *attribute tree* (d) and Figure 3(b)). The attribute trees can be reorganized by a functional way server according to a given viewpoint [12]. This step will be discussed in Section 4.

The modeling process discussed above is to describe a functional knowledge in a bottom-up manner from scratch. When the general knowledge of ways is available, the modeler can use it for describing the function decomposition tree and/or add a new way of function achievement to an existing general function decomposition tree or an existing *is-a* hierarchy.

Note that these types of trees concerning functions in Figure 1 are different from each other. The function decomposition tree (a) represents *is-achieved-by* (a kind of *part-of*) relations among functions. The *is-a* hierarchies of ways (c) represent an abstraction of the key information about how to achieve the function, while the *is-a* hierarchies in the functional concept ontology (e) represent abstractions of functions themselves, that is, the goals that are achieved. Moreover, the numbers of the ways for a function are huge in nature, while the numbers of functional concepts are small. However, it is not an easy task to distinguish a way from a function. We will discuss it in the next section.

3. Describing a function decomposition tree

A function decomposition tree represents "is-achieved-by" relations among functions. The macro-function is achieved by the sequence of sub(micro)-functions. This relation is a kind of "part-of" relations or aggregation relations among function. Function is defined as a black box, thus its relation of the input and the output of the macro-function should be equal to that of total of micro-functions. Although the structure of the function decomposition tree is matched with the structural (or topological) aggregation structure in many cases, they are sometimes different from each other [11]. There are temporal and causal relations among sub-functions.

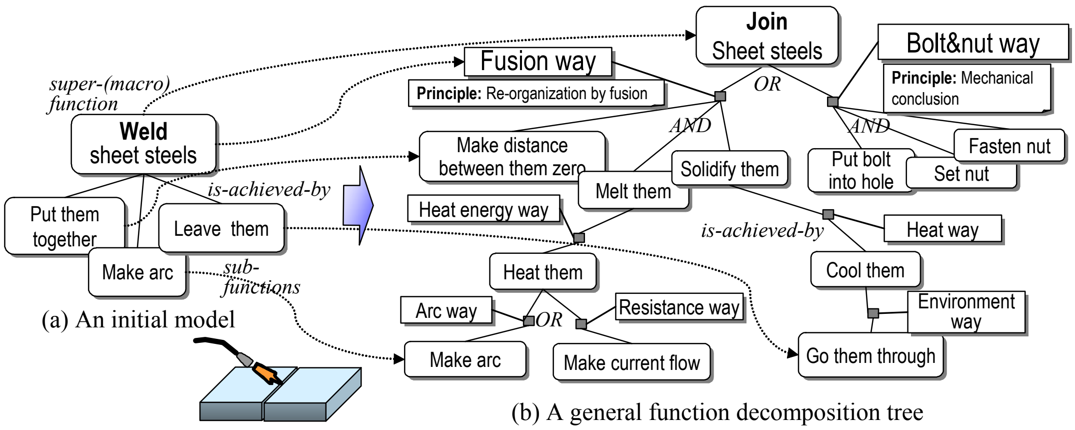
Although similar relations are found in literature such as [1,4,5,6], the major features of our knowledge modeling include (1) explicit conceptualization of "way", (2) the functional ontologies, and (3) general decomposition trees as follows. Firstly, we introduce the concept of "way of function achievement" as conceptualization of background knowledge of functional decomposition such as physical principles and theories as the basis of the achievement. On the other hand, we call the sequence of sub-functions *the method of the achievement*. A traditional functional decomposition model [1] represents only methods that represent "how" the macro-function is achieved, while the ways represent "why" the sequence of the sub-functions can achieve the macro-function. The conceptualization of way of achievement helps us detach "how to achieve and why" (method and way) from "what is intended to achieve" (function) as shown in an example below.

Secondly, we have developed the functional concept ontology ((e) in Figure 1) [11] which are detached from ways of function achievement. It defines about 220 concepts in 4 *is-a* hierarchies with clear operational relationship with objective behavior of a device. The base functions are categorized by kind of target operand (things to be changed by the function) such as substance, energy, information, force and motion. In order to capture functions consistently, it is based on an extended device ontology (f) [12]. Using these functional concepts as vocabulary, all the knowledge in Figure 1 is described. Although it may reduce the freedom of functional representation in comparison with hand-written functional models, it helps us avoid ad hoc modeling and obtain consistent functional models.

Lastly, a general function decomposition tree consists of possible ways of achievement of a function in OR relationship. It can be described from some functional decomposition trees with the same top-function. Alternatives from other knowledge sources are also added.

The modeling process consists of four steps; (1)an initial model using free words, (2)mapping to the controlled vocabulary in the functional concept ontology, (3)checking with modeling guidelines and (4)alignment of the functional concepts. In the second step, the operational definitions of the functional concepts enable a modeling support system to pick up the possible concepts according to the intended output (and input) states given by modelers. The guidelines for the third step are being developed and are concerned with agents and operands of functions, relations among sub-functions, and the "is-achieved-by" relations. They help a modeler capture functional structures based on the extended device ontology. For example, because sub-functions must contribute to achieve the macro-function clearly on the basis of the physical principles represented as the way of function achievement, a modeler should check existence of implicit functions (called A2 guideline). In the last step, associations between confusing functional concepts (called inappropriate associations) help us as discussed below.

Figure 2 shows an example of a modeling process, where the initial model (a) of a manufacturing facility is changed into a general function decomposition tree (b). Firstly, as mentioned in Introduction, the top-function "to weld" in the initial model should be decomposed into the "joining function" and "fusion way". The alternative ways such as the "bolts and nuts way" are also added in the general function decomposition tree with the OR relationship. The sub-functions in Figure 2(a) also should be changed. Firstly, a sub-function "to put them together" can be mapped into either "to unify" (it is defined as a change of two objects into one) or "to touch" (non-zero distance between two objects are changed into zero)



(a) An initial model

(b) A general function decomposition tree

Figure 2. An example of describing a general function decomposition tree from an initial model.

according to an inappropriate association. In this case, the designer's intension is clarified as "touch them each other". Secondly, against the A2 guideline discussed in the above, a sub-function "to make arc" does not directly contribute to the joining function. The missing two sub-functions, i.e., "to melt them" and "to heat them", are inserted as shown in Figure 2(b). These functions are supposed by designers implicitly in the initial model. Lastly, for "to leave them", there are also implicit sub-functions; "to solidify" and "to cool". Such modification enables us to add the alternative ways such as the resistance way for heating.

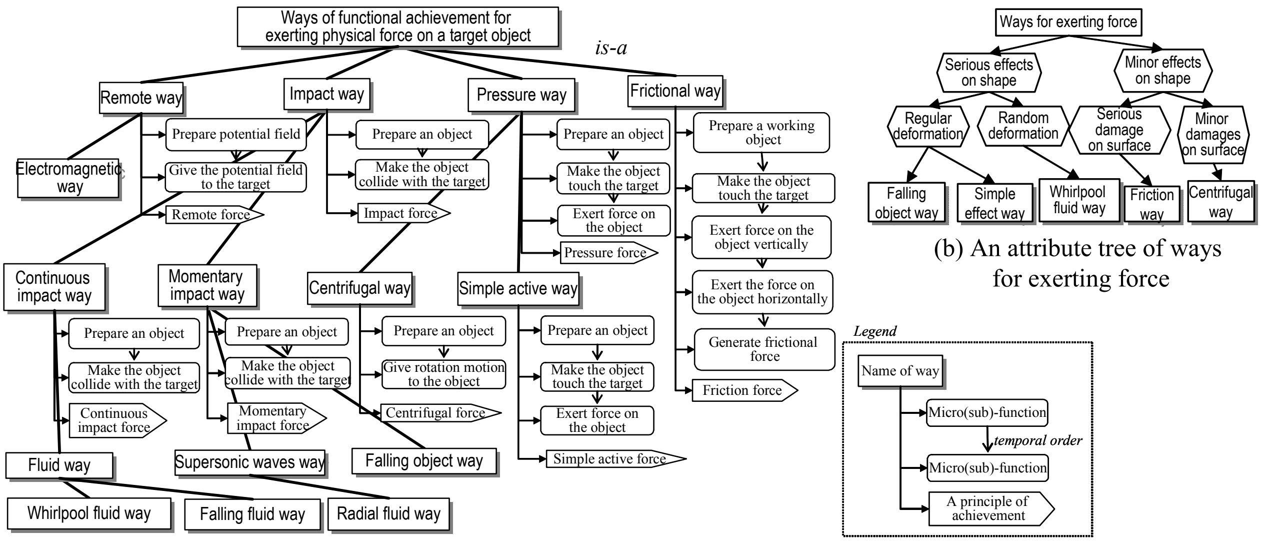
In text-books in the field, we find "the arc welding way", which is not a primitive way but a composite way that can be defined in a general decomposition tree by all the OR branches in a path from the root to a leaf node. The arc welding way is a composite of the "arc way" for heating, the "heat energy way" for melting and the "fusion way" for joining. Such composite ways often cause an inappropriate structure of conventional organization of the way knowledge. In our framework, they can be properly described as such composite ways in the general functional decomposition trees.

4. Generalizing concrete ways into generic ways

Each way is then generalized into a generic way independent of specific devices and operands. We call generic ways *functional way knowledge*. Its description consists of a macro-function, a set of sub(micro)-functions, temporal and causal constraints among sub-functions, principles of achievement, conditions for use of the way, and characteristics of the way. According to the specification of the conditions and the characteristics, the generic ways have several levels of generality, e.g., a way applicable to only a specific class of operands. Although it includes a description of the method of function achievement, we call it *"way"* focusing on the fact that it includes description of principle of the achievement.

The generic ways of achievement of a function are organized as an *is-a* hierarchy shown in Figure 1(c) according to the physical principles on which they are based. Because the principles are inherent properties of the ways, we can consider them to be organized in a straightforward *is-a* hierarchy. As an example, Figure 3(a) shows an *is-a* hierarchy of ways of achievement for "exerting physical force", in which ways are categorized into the abstract (highly generic) ways such as the impact way and the pressure way. On the other hand, for selection of ways, ways are classified according to their attributes in a form of so-called decision tree (we call it an attribute tree shown in Figure 1(d) and 3(b)). The branch nodes represent characteristics of ways. Each of the ways of connection is classified by values of such characteristics and appears as a leaf node. The structure of the attribute tree can be changed according to the purpose of the classification of interests. An attribute tree from the viewpoint of physical effects on the target objects is shown in Figure 3(b). Confusion of this difference has been one of the causes of the inappropriate organization of way knowledge.

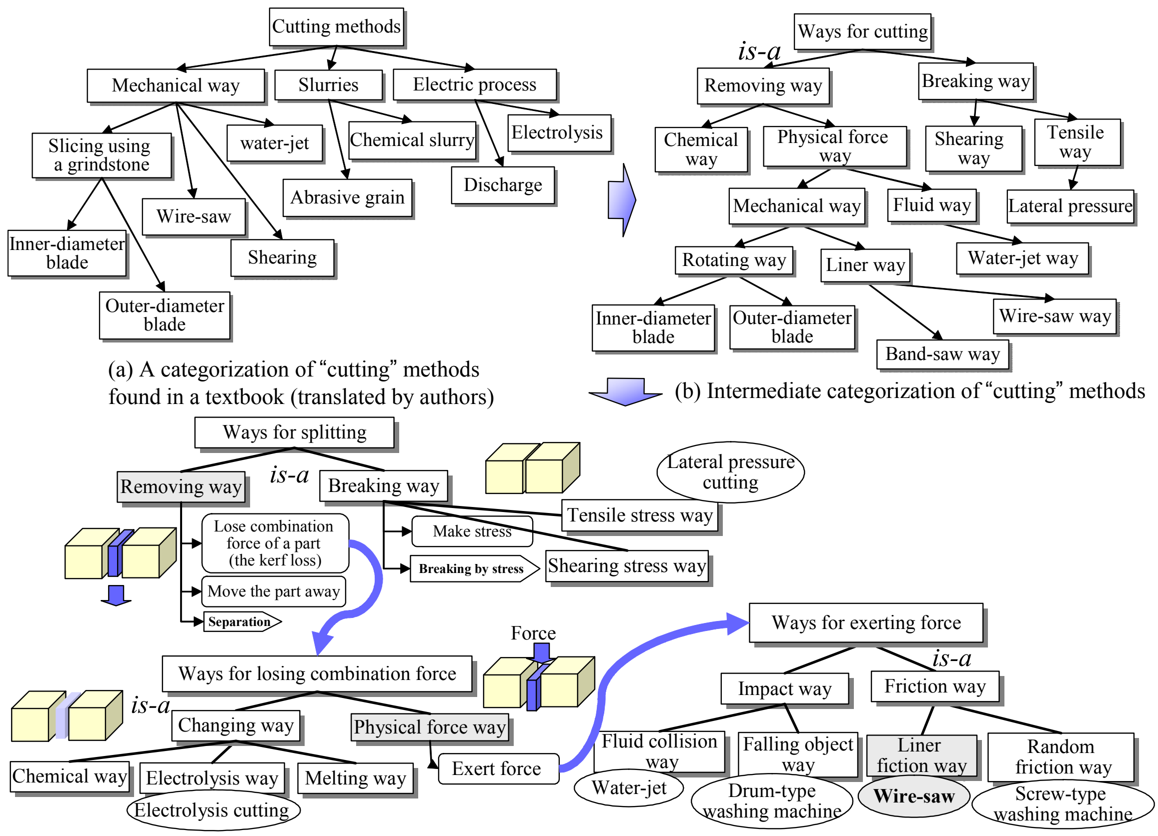
Here we show an organization of ways for “cutting” as an example, which is from our experience when we described a model of a wire-saw for cutting semiconductor ingots in a wafer production system (discussed in the next section). Firstly, Figure 4(a) shows an organization of ways of cutting which is found in a text-book in the field [16]. However, it mainly shows not principles but “what is used for”. The intermediate categorization made by



(b) An attribute tree of ways for exerting force

(a) An is-a hierarchy of ways for exerting force

Figure 3. An *is-a* hierarchy and an attribute tree of ways of function achievement for “exerting physical force”



(a) A categorization of “cutting” methods found in a textbook (translated by authors)

(b) Intermediate categorization of “cutting” methods

(c) A decomposed organization of the ways for cutting (portion)

Figure 4. An example of organizing generic ways in *is-a* hierarchies.

us (shown in Figure 4(b)) shows principles of achievement. However, for example, the water-jet way can be used for blowing something off. It suggests that the function achieved by the water-jet way is not the cutting function itself but its sub-function.

As a result shown in Figure 4(c), we decomposed the ways for cutting into some ways for three different functions; that is, “to split a thing into some parts”, “to lose combination force” and “to exert force”. The ways for exerting force in Figure 4(c) is a simplified part of one shown in Figure 3(a). For example, the wire-saw way is decomposed into three ways; the removing way for splitting, the physical force way for losing combination force of a part (the kerf loss), and the liner friction way for exerting force (a function decomposition tree of the wire-saw is shown in Figure 5 in the next section). Figure 4(c) shows examples of some slicing machines also. In this organization, difference between the wire-saw and other slicing machines such as the water-jet cutting and the electrolysis cutting are explicitly represented. Moreover, the ways for exerting force can be also used for washing machines. For example, in the screw-type washing machine, dirt is separated from cloth by the friction force which is caused by whirlpool fluid made by a rotating screw. It means that these pieces of knowledge are general and applicable to different domains.

5. Usage and deployment of the framework

Our framework is being deployed in the Production Systems Engineering Division of Sumitomo Electric Industries for sharing functional design knowledge of production systems. After one year study of our theory, the company started test use in May, 2001. Sumitomo engineers and we described (general) function decomposition trees of production facilities in production systems for semiconductors. As an example, Figure 5 shows the function decomposition tree of a wire saw for cutting ingots.

The experiential evaluation by the Sumitomo engineers was unanimously positive. They said that this framework enabled them to explicate the implicit knowledge possessed by each designer and to share it among team members. It was easy for designers to become familiar with the framework based on the device ontology. They developed a knowledge collecting software and decided to deploy it.

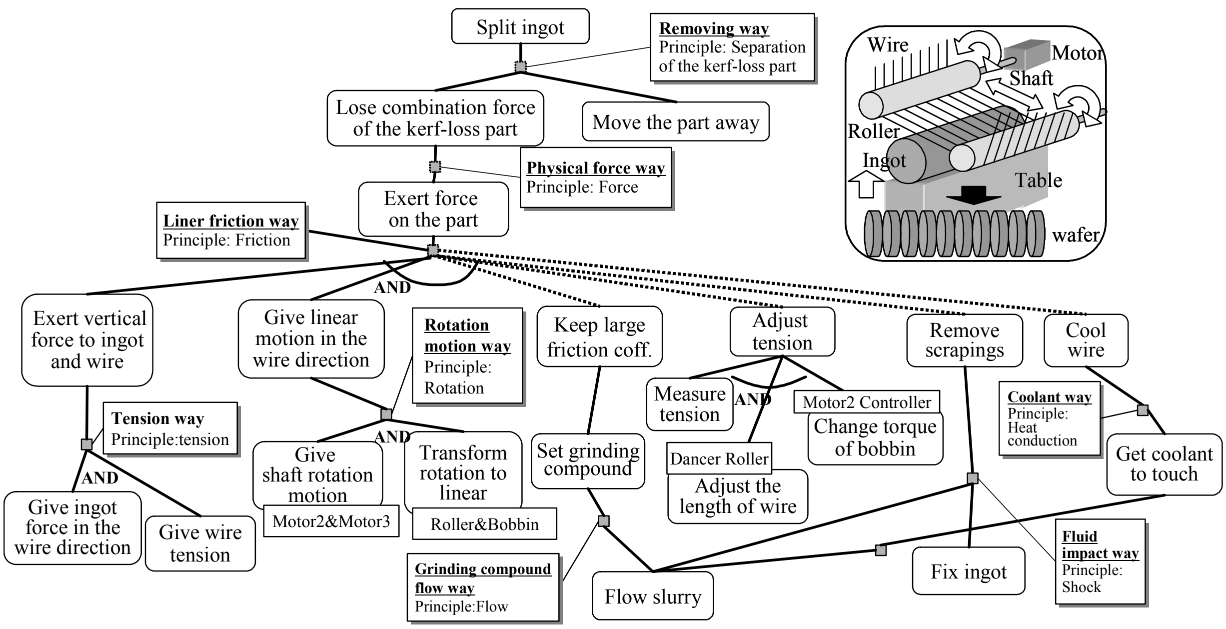


Figure 5. A function decomposition tree of a wire-saw for slicing ingots (portion).

Basically, for a target production facility (in general, it can be a product also), the usage of our framework is categorized into (1) to communicate with other designers about the target facility using its (general) function decomposition tree, (2) to explore causes of a problem of the facility using its function decomposition tree, and (3) to redesign (improve) the target facility using its function decomposition tree and general functional way knowledge. The following give summary of remarkable results in each type of usage in the deployment.

As one of the first usage, the models of ways of function achievement were used as *knowledge media* for collaborative work by people having different viewpoints such as manufacturing engineers, manufacturing equipment engineers, equipment operators and equipment maintainers. Although mutual understanding and collaboration among them was strongly required, it never happened. The use of our framework, however, enabled them understand and collaborate with each other in a facility improvement project. It turned out that the framework worked as a common vocabulary which lacked before.

As one of the second usage, a designer was not able to solve a problem of low quality of semiconductor wafers after 4-month investigation. By exploring causes of the problem in the model of ways of function achievement with a clear description of physical principles, he found a solution for the problem within 3 weeks.

As one of the last usage, a feasible new improvement of the wire-saw was found from the knowledge-base by adopting the way of using magnetic fluid for controlling tension of the wire. This can be done by applying a way originating from the textile industry to the semiconductor industry. This indicates feasibility of our framework for general functional knowledge.

The success factors of the deployment are summarized as follows; (1)clear discrimination between function (goal) and way (how to achieve the goal) which contributes to reusability of the knowledge, and (2)clear discrimination among *is-a* and *part-of* relations, that is, the *is-a* hierarchy of functions and that of ways, and the *is-achieved-by* (a kind of *part-of*) hierarchy of function, and (3)explicit viewpoint specification by the extended device ontology.

6. Related work and discussion

As discussed in Section 3 and 4, the way of function achievement plays a crucial role in both describing a model of a concrete product and organizing a generic knowledge. Although a similar idea of the function decomposition is discussed by Malmqvist [17], he focuses on specific product models and there is no organization of general knowledge.

In design literature such as [1], generic patterns of function achievement so-called design catalogs can be found. However, they mainly concentrate on concrete mechanical pairs. In [4, 5,6], similar ideas to our idea of way of functional achievement for general functions are discussed. The research on design processes [18] points out that functional decomposition is not done solely in the functional space but also by going back and forth between the functional, behavioral and structural spaces. Thus, such functional knowledge includes behavioral and/or structural information. The design prototypes [5] include structural decomposition as well as functional decomposition. In the FBS modelling framework [4], a function prototype includes the physical feathers of behavior realizing the function as well as generic function decomposition. Our description of ways tries to maximize its generality by pointing partial (and abstract) information of structure and behavior.

Moreover, use of generic functional concepts in the *is-a* hierarchies in the functional concept ontology facilitates reuse of the knowledge in different domains. In IDEAL [6], generic teleological mechanisms (GTM) generalized from case-specific SBF models are used (modified) in design for a different context based on analogy. In our approach based on the limited set of functional concepts, the ways of function achievement are organized in *is-a* hierarchies. Designers can explore them in several abstract levels explicitly.

Such knowledge can facilitate innovative design, because many innovative designs are based on techniques known in different domains. TechOptimizer [19] is a software product based on a theory for innovative design (TRIZ), which contains generic principles of invention. However, it just searches highly abstract principles based on given criteria.

Limitation of our ontologies and application domain

We cannot claim completeness of the concepts in our functional concept ontology. Note that we did not define domain-specific functions but general functions that are common in many domains. Although one might think that the set of functional concepts is huge, not the set of function but of the set of ways of function achievement is very large. In fact, in Value Engineering research [9], 158 verbs are proposed as a standard general set for representing functions of artifact. Although it includes functions for human sense as well, we concentrate on functions changing physical attributes.

The ontologies have been applied to modeling of a power plant, an oil refinery plant, a chemical plant, a washing machine, a printing device, and manufacturing processes. Their models include changes of thermal energy, flow rate, and ingredients of fluid, force and motion of objects. The current functional concept ontology can describe simple mechanical products, though it does not cover static force balancing and complex mechanical phenomena based on the shape of objects.

Further research: modeling of other-than-intended and/or other-than-artifact behaviors

In this paper, we concentrate on functions, i.e., the teleological interpretation of the *intended* behaviors, of *artifacts*. In the collaborative research with the ICA group of Delft University of Technology, modeling of *other-than-intended* or *other-than-artifact* behaviors is discussed in [20]. The former includes faults of devices and undesirable states which decrease the efficiency (e.g., time) of functioning and/or quality of the operands. The latter includes user actions and effects by the environment, which also can be unintended by designer and/or cause undesirable states. Especially, it is important to describe the design rationale of functions for avoiding the unintended user action itself and/or the harmful effects caused by such an action. For example, the drip-stop function of a coffee maker is for avoiding possible short-circuits caused by user's early jug removal [20]. We are investigating on a modeling framework of undesirable state and such functions.

Such modeling of other-than-artifact behaviors requires a framework of model generation and simulation in order to cope with general situation (configuration) of artifacts, users and the environment in such a manner that is less dependent on specific geometry. Such a modeling technique based on the nucleus modeling is discussed in [21].

7. Summary

The contribution of this research can be summarized as the framework for description of sharable knowledge about functional decomposition. In this paper, we discussed its modeling process from a functional model of a specific artifact (called the function decomposition tree) to generic knowledge in *is-a* hierarchies. The key issues are explicit conceptualization of the way of function achievement, the use of functional ontologies, and discrimination between inherent organization and viewpoint-dependent organization (called attribute trees). The successful deployment of our framework in the production company was also discussed.

Acknowledgements: The research issues discussed in Section 6 has been explored as a part of the collaborative research with Mr. Wilfred van der Vegte and Prof. Imre Horváth, Delft University of Technology. The authors would like to thank Mariko Yoshikawa, Tomonobu Takahashi, Toshinobu Kasai and Kouji Kozaki for their contributions. Special thanks go to Dr. Masayoshi Fuse and Mr. Masakazu Kashiwase, Sumitomo Electric Industries Ltd., for their cooperation in the deployment of our methods in the production systems.

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