Applied Ontology 1 (2005/2006) 237–262
IOS Press

An ontological model of device function: industrial deployment and lessons learned

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Abstract. Functionality is one of the key concepts of knowledge about artifacts. Functional knowledge shows a part of designer's intention (so-called design rationale), and thus its sharing among engineers plays a crucial role in team-activities in engineering practice. Aiming at promoting engineering knowledge management, we have developed an ontological modeling framework of functional knowledge, which includes an ontology of device and function and a controlled vocabulary. This framework has been successfully deployed in a manufacturing company in daily engineering activities. In the first part of this paper, we discuss some ontological issues concerning the functionality of artifacts, and redefine the notion of function as a role. In the second part, we discuss some lessons learned in the actual deployment of this framework and two extensions based on such experience. One extension is a lexical layer for functional terms intended to help engineers select appropriate functional concepts and to facilitate the use of domain-specific terms familiar to them. The other extension is the establishment of ontological modeling guidelines, which help engineers commit to the relevant ontologies and describe models compliant with them.

Keywords: Engineering, ontologies, functionality, knowledge management, engineering design, role

1. Introduction

Functionality[1] is one of the key aspects of artifacts. While there is no common agreement on its definition and its representation, it is widely accepted that the function of an artifact is tightly related to the intention of designers or users (de Kleer, 1984; Chandrasekaran et al., 1993; Umeda & Tomiyama, 1997; Chittaro & Kumar, 1997; Hubka & Eder, 2001; Stone & Chakrabarti, 2005). Intuitively, a function of a product explains what users can get using it, i.e., effects or utility of the artifact. The function of a component embedded in a system explains how it contributes to achieving the overall system's function (i.e., "how things work"). In contrast to objective data such as shape and structure, recognizing the function of an artifact usually depends on the particular system considered, its environment, a specific situation, or usage.

In engineering situations, functional knowledge is an important constituent for engineering knowledge management. It plays a crucial role in many engineering activities such as designing, manufacturing and maintenance. Especially, conceptual design can be viewed as an activity to develop a functional structure (i.e., relationships among functions of components and a system) and mapping relations between functions and physical structures which can realize them. Functional knowledge represents a part of designer's intention – so-called *design rationale* (DR) (Chandrasekaran et al., 1993; Lee, 1997), which

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[1] In this article, the term "function" is used as the same as "functionality".

gives justification of the current design, including reasons of existence of a component or a sub-system in the system. Explicit representation of DR facilitates engineering activities such as design review, product improvement, and facility maintenance. For example, in design review to doublecheck an original design by a team of designers, an explicit description of the original designer's intentions helps other people understand the original design more effectively. In facility maintenance, in order to adjust a certain working parameter a maintenance engineer should understand the reasons of the current value, which are a result of the designer's decisions.

Nevertheless, it is well known that sharing knowledge about function is difficult in practice, which has been confirmed by our experience of collaborative research with a production company. Few CAD/CAM/PDM systems deal with such subjective knowledge. Thus, engineers have to rely on documents in natural language. Engineers have been regularly writing various kinds of technical reports/documents and have stored much of those in databases. Unfortunately, however, few of such technical documents have been efficiently reused. One of the reasons for this difficulty is lack of *semantic constraints* for functional knowledge. By semantic constraints we mean here those guidelines or restrictions which help a knowledge-author to describe models complying to the conceptualization to which the author commits. Without such semantic constraints, functional models tend to be ad hoc, specific to the target product, and hence not reusable. Although much research on functionality has been conducted in areas such as functional representation (Sembugamoorthy & Chandrasekaran, 1986; Keuneke, 1991; Chittaro et al., 1993; Lind, 1994; Umeda et al., 1996), engineering design (Pahl & Beitz, 1988; Gero, 1990; Hubka & Eder, 1988, 2001; Hirtz et al., 2002) and value engineering (Miles, 1961), there is no common definition of the concept of function itself (Umeda & Tomiyama, 1997; Chittaro & Kumar, 1997; Hubka & Eder, 2001), nor a clear categorization of relationships among functions. In sum, current research results on knowledge sharing are not enough for deriving effective guidelines as semantic constraints. We argue that an ontology of functionality can provide semantic constraints on knowledge-contents as "meta knowledge". We will discuss its needs in the next section.

The goal of our research is to facilitate engineering knowledge management of functional knowledge by providing an ontological modeling framework that implements such semantic constraints. Ontology about functionality aims at specifying a *conceptual viewpoint* for capturing the target world and a *controlled vocabulary* to describe the knowledge at an appropriate level of abstraction. Much work on engineering domain ontologies has been done (Cutkosky et al., 1993; Gruber & Olsen, 1994; Borst et al., 1997; López et al., 1999; Yoshioka et al., 2004). Many of them aim at improvement of interoperability among agents or tools (Cutkosky et al., 1993; Yoshioka et al., 2004). Rather, we aim at "ontology as meta knowledge" as discussed above. One remarkable example of meta-knowledge type is the PhysSys ontology (Borst et al., 1997). It, however, has no ontology for functions from the teleological viewpoint.

The authors have been involved in ontology-based modeling of physical systems for many years and have established an ontological framework for functional knowledge (Kitamura et al., 2002; Kitamura & Mizoguchi, 2003, 2004a). This framework includes an ontology of device and function as a conceptual viewpoint and a functional concept ontology as a controlled vocabulary. A knowledge management software called SOFAST based on such framework has been successfully deployed in a manufacturing company in Japan for sharing functional knowledge (Kitamura et al., 2004).

This paper reports on extensions of these previous efforts. Its contribution is twofold. In the first part we discuss some ontological issues concerning the functionality of artifacts, investigating the requirements of an ontology of function based on the concept of "role" adopted Ontological Engineering. Then, we refine our previous definition of function reported in Kitamura et al. (2002).

In the second part of this paper we discuss lessons learned in the deployment and two extensions based on such experience. In the deployment, it turned out that engineers have difficulties in selecting appropriate generic types of functions and describing functional models compliant with the ontologies. The extensions proposed to reduce these difficulties are a lexical layer for functional terms, and ontological modeling guidelines, respectively. The former provides multiple mapping relations between types of functions and superficial labels (names) for denoting the types. A new version of SOFAST was developed in order to help engineers to select a function when they describe functional knowledge, and to search for a function independently of any difference of superficial labels. The latter provides knowledge authors with a checklist for revising their functional models in order to describe models compliant with the ontologies.

This paper is organized as follows. Section 2 discusses needs of ontologies for functionality. Section 3 discusses the requirements of an ontology of function. Section 4 presents our ontologies about functions. The experience in the deployment is discussed in Section 5. Section 5.1 summaries the process of the deployment and the usages discussed in (Kitamura et al., 2004). The effects of the ontologies are discussed in Section 5.2. Section 5.3 discusses the lessons learned in the deployment, which includes success factors of the deployment and difficulties faced in the deployment. Section 6 presents the extensions to reduce the difficulties. Then, related work is discussed followed by some concluding remarks.

2. Current challenges in functional knowledge modelling and ontology as its solution

This section presents two examples that demonstrate the difficulty in functional knowledge modeling and then proposes use of ontologies as a solution. Firstly, functionality in Value Engineering is represented in "verb+noun" style (Miles, 1961) and on the basis of this, one might describe "to weld metals" as a function of a welding machine. However, "to weld metals" implies both the metals are joined and their parts are fused. From the viewpoint of functionality in manufacturing, joining is only the goal the designer intends to attain ("what to achieve"), while the fusion can be regarded as a characteristic of "how to achieve that goal". In fact, the same goal, say, "to join", can be achieved in different ways (e.g., using nuts & bolts) without the fusion. If a function of the welding machine is described as "to join", the commonality between two facilities can be found. This issue is not a terminological but *ontological* in order to distinguish "what to achieve" from "how to achieve". We distinguish terminological problems, for instance, to use a word "to fix" instead of "to join" for representing the same concept. Thus, this example demonstrates the importance of functionality in reusable functional knowledge.

The well-known systematic design methodology in (Pahl & Beitz, 1988), on the other hand, includes hierarchical structures of functionality based on input–output relations (so-called functional decomposition). However, it is not easy to describe such functional models. For the welding machine example, one might describe "to put objects together", "to make an arc", and "to leave them" as sub-functions (decomposed micro-functions) of the goal function "to join". These sub-functions certainly describe decomposition of the input–output relation. However, there is an implicit intermediate function "to heat objects" between "to make an arc" and the goal function. In fact, "to heat objects" can be achieved by "to make current flow" instead of "to make an arc". Moreover there is another implicit function "to melt objects" as the goal function of the heating function. This second example demonstrates the importance of practical specifications on semantics for functional decomposition, in addition to standard specifications as decomposition of input–output.

This suggests the necessity for semantic specifications of functional knowledge's content to help knowledge authors to describe knowledge accordingly to their conceptualization. This is consistent

with the view of ontologies (Mizoguchi, 2005) as "explicit specifications of conceptualization" (Gruber, 1993). An ontology about functionality specifies a *conceptual viewpoint* and a *controlled vocabulary* for functional knowledge. The former provides guidelines or constraints on modeling, which help knowledge authors to describe functional knowledge consistently, and especially to distinguish "what to achieve" from "how to achieve". On the other hand, the latter provides a systematized set of generic verbs representing functionality of devices at an appropriate level of abstraction.

3. Ontological issues of function

This section discusses ontological issues as requirements for reusable and consistent functional knowledge. Our goal here is to define functions, generic functions, and relationships between functions clearly and operationally.

3.1. Definition of function with behavior

For clear definitions of functionality, the relationship with "behavior" plays a crucial role. The distinction between function and behavior here originates from the qualitative reasoning (QR) research such as de Kleer & Brown (1984). The *behavior* of a device here represents temporal changes of the properties of a physical entity (that we call *operand*) which is different from the device. It is objective and independent of the *context* which includes designer's intention, user's aims and the system in which the entity is embedded. In QR, in order to realize reusability and composability of the component model, context-dependent information is carefully excluded. This has been called the No-Function-In-Structure principle[2] in (de Kleer & Brown, 1984).

In comparison with behavior, *function* is related to the intention of a designer or a user (i.e., it has a teleological interpretation) and hence is context-dependent. A behavior can implement different functions according to the context. For example, a heat exchanger can be used as a heater or a radiator. The behavior is the same in any context, that is, a heat flow from the warmer fluid to the colder one, where the flows of fluid are operands. The functions of the heater and the radiator can be "to give heat" and "to remove heat", respectively. This difference of functions is dependent on the embedded system.

Thus, the first issue is to clarify this *teleological interpretation relation* between behavior and function and to define the notion of function on the basis of this relationship. In the literature, this relationship is defined as "means and ends" (Lind, 1994), "F-B relationship" (Umeda et al., 1996), "aims-means" (Hubka & Eder, 1988) (this includes design requirements as well) or "causal patterns" (de Kleer, 1984). Note however that the well-established standard taxonomy for functions, called *functional basis*, adopted by the NIST Design Repository Project (Hirtz et al., 2002) lacks clear relationship with objective behaviors based on such teleological relationship.

In order to clarify this relationship and to define functions operationally, our approach is to describe a function as "behavior plus information for teleological interpretation" in terms of a set of primitives (called *functional toppings*) as discussed in Section 4.1. Moreover, we define generic functions as constraints on such information as discussed in Section 4.2.

[2] Although a behavioral model depends on modeler's assumptions and viewpoint for capturing the target world as the same as all information models do, the concept of "behavior" itself represents context-independent changes.

3.2. Function as a role

The second issue related to the definition of function is the "*role*" concept in ontological engineering research. Intuitively, a *role* is something that can be *played by* an entity in a context. Precisely, in Sowa (1995), a role is a *secondness* concept which is dependent on a pattern of relationship. In Masolo et al. (2004), a role is *anti-rigid* (i.e., contingent with respect to identity), *dynamic* (temporary and multiple), and *founded* (i.e., is an extrinsic property defined with reference to an external concept). Similarly to these definitions, by role we mean here such a concept that an entity plays in a specific *context* and cannot be defined without mentioning external concepts (Mizoguchi et al., 2000; Kozaki et al., 2002; Sunagawa et al., 2006). We distinguish *role* (something to be played) from *role-holder* (something actually playing a specific role). This role-holder is different from *role-player* which can play a role only potentially. For example, the "husband role" (a role concept) is played by a member x of the class "man" (the class to which the player of this role is constrained) in a "marriage" relation (this relation gives the role context). The entity x that is playing the "husband role" is the "role holder" and is a member of "husband" (namely, the class-equivalent[3] of man with husband role). A member x of the class "man" is a *potential* player for the "husband role". The ontology editor used in our environment for building/using ontologies named Hozo has a capability to deal with roles (Kozaki et al., 2002; Sunagawa et al., 2006).

Let us analyze the properties of a function. Firstly, a function (and a behavior as its basis) is *founded*, since the function of an artifact affects an entity (the operand) other than the artifact itself and causes temporal changes of such an entity (this is the *behavior of the device* in the sense of Section 3.1). For example, a radiator decreases the temperature of the warmer fluid and the definition of the removing-heat function refers to the change of the warmer fluid's temperatures as input and output. Thus, the definition of a function of an artifact requires an operand as an external entity.

As discussed in Section 3.1, a *behavior* can perform different *functions* according to teleological contexts. By definition, a behavior is objective and thus does not lose identity by the change of function. Thus, the property a behavior has to implement a certain function is *anti-rigid*. Moreover, a function can be performed (realized) by different behaviors. A function is associated with specific constraints on a part of behaviors to realize the function. A behavior can perform multiple functions simultaneously. Thus, a function is dynamic and multiple.

A function can be defined as a *role played by a behavior in a teleological context*. We say that "a behavior can play a function role". If a device performs a behavior and the behavior plays a *function role* in a context, then the device plays a *function-performer role* in the context. For example, the heat-exchange behavior plays the removing-heat *function role* and then a heat exchanger plays the *function-performer role* of removing-heat as a radiator.

The teleological context for an engineering system can be determined according to a designer's intention or a user's intention (i.e., how to use it). The context for a component embedded in a system is the configuration of the system (precisely, as discussed in Sections 3.4 and 4.1, a functional structure).

In the literature, similar concepts are discussed. Chandrasekaran & Josephson (2000) use the concept of *role* as implying *natural* (without human intention) effects on environment (e.g., the role of a cloud is to give rain) and define *function* as "role + intention". In the EPISTLE Framework, the concept of *facility* is defined as a functional thing, i.e., the capability to perform a function and a service (West, 2004). Fan et al. define the *purpose* of an artifact as a *default role* which is expected to be played by the artifact (Fan et al., 2001). Breuker & Hoekstra (2004) point out the notion of function as role and discuss *mental*

[3] It is an abstraction of individuals (men) playing a specific role. See details (Kozaki et al., 2002; Sunagawa et al., 2006).

roles in law. Garbacz (2005) points out that an artifact's function is a *state of affairs*, which represents a connection between objects and processes (in our terminology, operands and behavior). He identifies some upper-level functions based on DOLCE. Vermaas (2005) describes a function as a relationship among an agent, a use plan, a physicochemical capacity and a justifying account.

In summary, the second issue concerns the definition of function as a role of a behavior. Such definition requires a description of the context for functional interpretation. The *functional topping* is a localized representation of the context. Our definition of function as a role of a behavior with functional context is discussed in Section 4.1.

3.3. Device ontology and entity's roles

For consistent representation of functions, the consistent representation of behavior and system is a very important issue as well. In the design literature, the German systematic design approach (Pahl & Beitz, 1988) has provided us with a basic viewpoint to capture functions as mentioned in Section 2, in which functions are regarded as the input–output relations of a black-box. The black-boxes can be connected and aggregated. Such a device-centered viewpoint originating from systems dynamics theory is called *device ontology* here. Similar ontologies have been established in the literature (de Kleer & Brown, 1984; Gruber & Olsen, 1994; Borst et al., 1997). A device ontology is suitable as a basis for establishing an ontology of functions, since functions are usually considered as what components or devices achieve.

The definition of the device ontology also requires the representation of "roles". Let us consider a manufacturing machine called a wire-saw, which is designed to slice a semiconductor ingot into wafers using a wire moved by rollers. To assign a role to this wire is not trivial. It exerts force on the ingots as a *device*, and is moved by rollers as *operand*. In order to assign roles to entities in a consistent manner, we have to maintain the relationship among entity, role and behavior. We will revisit this example in Section 5.2.

Thus, the third issue is to establish a *role assignment system* which helps model designers to assign roles to entities consistently. As discussed in Section 4.1, our approach is to extend the device ontology proposed in (de Kleer & Brown, 1984) by redefining *behavior*, *conduit* (a subtype of *device*) and *medium* (a subtype of *operand*) for a richer role assignment system.

3.4. "is-a" and "part-of" relations of function

The German systematic design approach (Pahl & Beitz, 1988) provides a fundamental relationship among function as well, so-called *function decomposition* as mentioned in Section 2. It represents how a function is achieved by a series of sub-functions which are finer-grained functions. We call the combination of a parent function and a series of children functions "*is-achieved-by*" relation, which is a kind of "part-of" relation. Usually (but not always), this decomposition corresponds to the whole-part (*aggregation*) hierarchy of physical structures of devices, that is, the whole system, sub-systems and components. In the literature, this relation has been captured as a whole-part relation (Lind, 1994), as a "degree of complexity" (Hubka & Eder, 1988) and as a function decomposition (Pahl & Beitz, 1988).

On the other hand, we can consider the "*is-a*" relation among functions. It can help representing generic or abstract concepts of functionality. Pahl & Beitz (1988) defined highly-abstracted functions (called generally-valid functions). Hubka & Eder (1988) identified the hierarchy for the "degree of abstraction" of functions which represents the specialization of functions with additional conditions. Such

conditions, however, may sometimes (not always) include the characteristics of a specific method of achieving a function such as "transportation by sea" (Hubka & Eder, 1988), presenting therefore the same difficulty as the "welding" discussed in Section 2.

It is not easy to distinguish the relationships among functions, that is, *part-of*, *is-a*, and the *teleological interpretation* (discussed in Section 3.1). One of the reasons is that whenever a function is achieved, its superordinate functions in the *is-a* hierarchy are also achieved. Papers such as (Sembugamoorthy & Chandrasekaran, 1986) do not distinguish *teleological interpretation* from the *part-of* relation and thus claim that "behavior" is how to achieve a function, where the distinction between behavior and function is relative.

In summary, the fourth issue is to clarify the relationships between functions such as *part-of* and *is-a* and to find descriptors of the *teleological interpretation*. We introduce the concept of *way of function achievement* as a conceptualization of the *part-of* relation. Moreover, we define *is-a* relations among the ways of function achievement as discussed in the next Section.

4. Ontologies for functional knowledge

This section presents an ontology of device and function (Section 4.1) and a functional concept ontology (Section 4.2), and introduces the notion of functional knowledge based on these ontologies (Sections 4.3 and 4.4).

4.1. An ontology of device and function

Our ontologies have been defined by means of an ontology editor in an environment for building/using ontologies named Hozo (Kozaki et al., 2002; Sunagawa et al., 2006). Figure 1 shows an example of definition of a role concept, and Fig. 2 shows a portion of an ontology of device and function. The ontology editor basically supports frame-based representation with slots. Concepts are represented as frames (denoted by nodes in Figs 1 and 2) with slots (right-angled link) and the *is-a* relations among concepts (straight link with "is-a"). Concepts are categorized into "wholeness concepts" composed of part concepts and "relational concepts". A wholeness concept has slots for part concepts (part-of relation denoted by a right-angled link with "p/o") and slots for attributes ("a/o"). A relational concept has slots

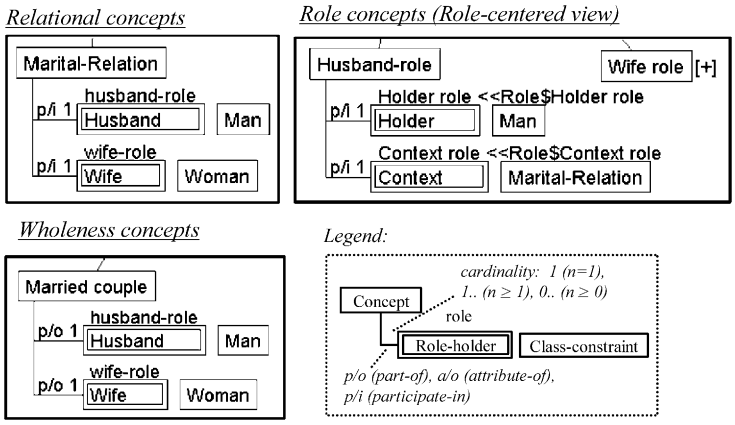


Fig. 1. Example of definition of a role concept (husband role) in Hozo.

for participant concepts (participate-in relation. denoted by "p/i") as well as attribute-slots. Figure 1 shows an example of definition of the husband role discussed in Section 3.2 (i.e., a *husband* (role holder) is defined as a *man* (class constraint) playing a *husband role*) in the "marital relation" concept. The upper right part of Fig. 1 shows its definition from a role-centered view. It is defined also in the "married couple" which is a wholeness concept corresponding to the "marital relation".

The ontology of device and function consists of an extended device ontology and an ontology of function. Figure 2 includes a portion of an upper-level ontology, by which we intend not to claim a generic upper-level structure but to clarify the meaning of the concepts in the ontology of device and function.

As mentioned in the previous section, one of the key concepts is *behavior,* which represents objective temporal changes of physical qualities of a physical entity. In Fig. 2(a), device's *behavior* is defined as temporal change of another *physical-entity* called an *operand*. The *device* is defined as a role-holder played by a *physical-entity*, which operates on the *operand* and changes its *physical-attributes*. The *operand* is something that flows through the device and is affected by the device. Thus, it is defined as another role-holder in the *behavior*. The *operand role* can be played by fluid, energy, motion, force, or information. The temporal change of *operands* is represented as a pair of *physical-states* as input and output of the device, each of which represents a value of a *physical-attribute* at a *port* of the device. A *port* of a device is a virtual interface for propagation of physical-attributes' values to another device. Each device is connected to each other through its input and output *ports* (Fig. 2(b)). Thus, the *behavior* represents objective conceptualization of its input–output relation as a black box. From the viewpoint of causality, as shown in Fig. 2(a), the changes in a behavior are caused by sub-behaviors (we call motion), which are a sequence of finer-grained behaviors.

The *behavior* is defined as a sub-type of *occurrent* (i.e., an entity has time-dependent part), *active* (i.e., change of attribute's value in certain time-interval) and *action* (i.e., process with an agent (i.e., actor, subject) who makes the process happen). Thus, it is disjoint from continuant, stative (i.e., a set of attribute-value pairs of an entity or entities at a time-point), and phenomena (i.e., process with participants without specific agent), respectively. Although it has the rather general label "behavior", it is specialized for device-oriented modeling and therefore related to the input–output relation of a device which represents changes of flowing entities (operands) as discussed above.

We defined rich types of behavior, conduit, and medium. We categorized the meanings of behavior into four types (from B0 to B3) (Kitamura & Mizoguchi, 2004a). The definition of behavior above (i.e., behavior based on *states* of the flowing *operands* at *ports* of *a device*) is called *B1-behaviour* in the terminology of (Kitamura & Mizoguchi, 2004a). A *conduit* (e.g., a pipe and a shaft) is defined as a special device that transmits an operand without any change in an ideal situation. A *medium* (e.g., steam for heat energy) is something that holds an operand and enables it to flow between devices. A medium role and a conduit role can be played by an entity simultaneously, although a device role and an operand role cannot. Such multiple role-playing is a solution for the issue in Section 3.3. We shall revisit this issue in Section 5.2.

A (base-)function role is defined as a role concept which is played by a *behavior* under a *function-context* (Fig. 2(c)). In the function-context, there is a *function-performing relation* among two physical entities and a behavior (Fig. 2(d)). In the relation, the behavior plays a base-function role, which is called a base-function role holder (Fig. 2(e)).

The *function-context* represents the teleological situation for specific goals in which a function is defined. It has two subclasses; that is, *system-function-context* and *user-function-context,* as shown in Fig. 2(f). The system-function-context is for a function of a component embedded in a system. It can be

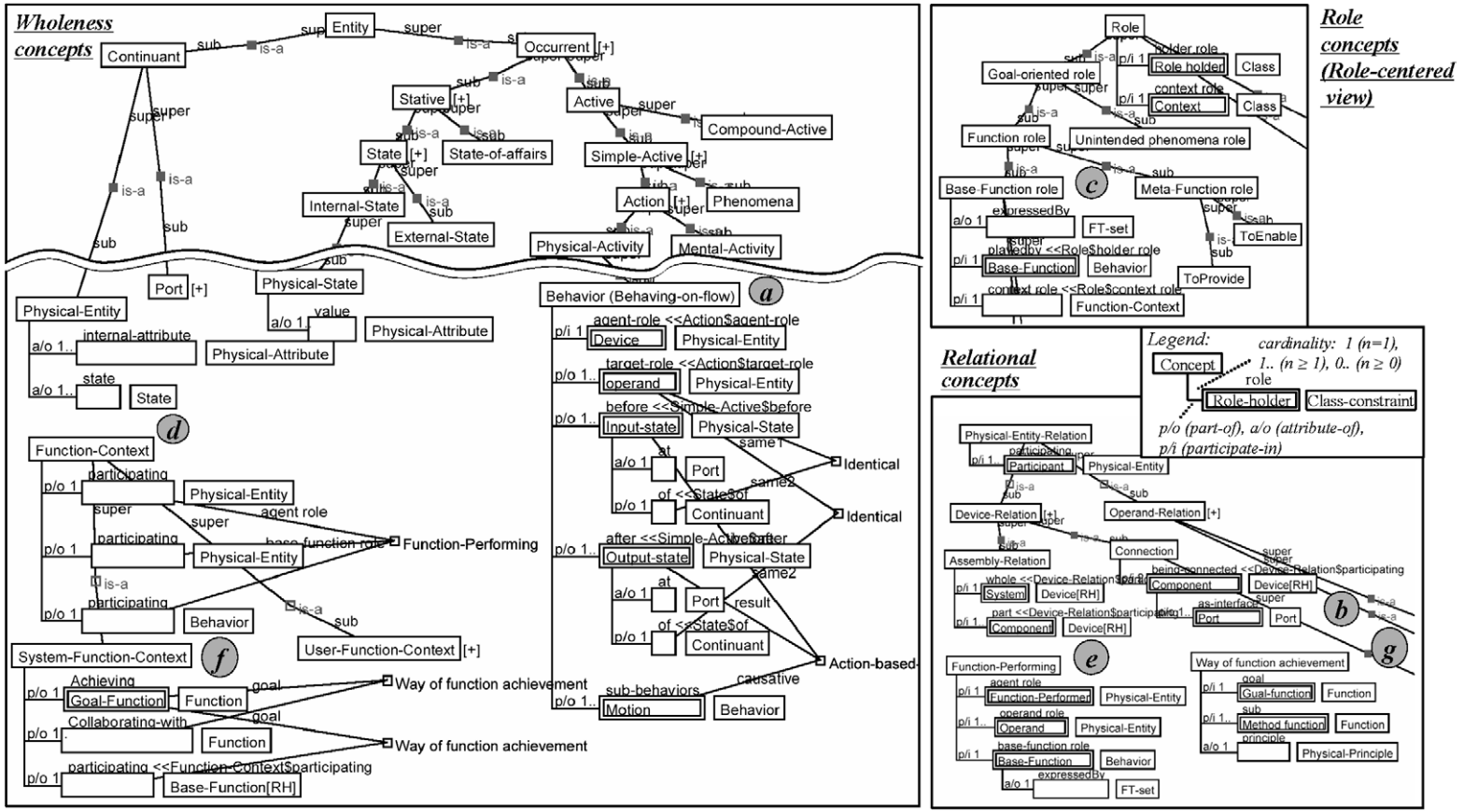


Fig. 2. A portion of an ontology of device-centered behavior and function in Hozo.

determined by the system's function and by the functions of other components connected to the component. A component's function, together with other component's functions (we call *method function*) achieves the system's function (*goal function*). In Fig. 2(g), the achievement relation is defined as a relational concept named "*way of function achievement*" relation. It has two *participant* slots; that is, a function with the *goal function role* and a list of functions with *the method function role*. It is used in the definition of the *system-function-context* as a restriction, which states that a base-function in the context should play a *method function role* for a *goal function*. (the third slot of the *system-function-context* shown in Fig. 2(f)). The base-function (a role holder) is inherited from the third slot of the *function-context* shown in Fig. 2(d), which states that a behavior plays both a *participating role* in the *function-context* and a *base-function role* in the *function-performing* relation discussed above.

These definitions are a more detailed version of our previous definition published in Sasajima et al. (1995), Kitamura et al. (2002), where a function was defined as a teleological interpretation of a *B1-behavior* under *a goal*. The "goal" of this previous version is redefined here as the function-context in detail. The "interpretation" is redefined here as the role recognition of the behavior in the function context. The additional information for the role recognition of behavior can be described using *functional toppings (FTs)*, that is, *Obj-Focus, O-Focus, P-Focus* and *Necessity*. These FTs are a kind of "tags" which provide behavior with additional meaning. They represent information about an *operand* that the designer intends to change (focus of intention). *Obj-Focus* specifies its kind such as substance or energy. *O-Focus* specifies the kind of physical attributes to change (such as temperature or phase). *P-Focus* specifies the ports and represents the focus of a flow of operand or medium. *Necessity* specifies the necessity of *operands* in the context. Such definition of function addresses the first and the second issues discussed in Section 3.

In the example of the heat exchanger mentioned in Section 3.1, the exchanger's behavior is described as a thermal energy flow between two medium flows. The giving-heat function can be represented as: (1) *O-Focus* on temperature and (2) *P-Focus* on the medium flow[4] which receives heat (heat destination). On the other hand, the removing-heat function can be represented as (1) the same *O-Focus*, (2) *P-Focus* on another source medium-flow which releases the heat energy and (3) the heat energy is not necessary (*Necessity*). Such functional toppings show the difference between these two functional interpretations. See our previous paper for representation details (Kitamura et al., 2002).

The values of the functional toppings are determined according to the function-context. The functional toppings (FTs) are localized representations of the surrounding context of the component. This localization contributes to obedience to the No-Function-In-Structure principle discussed in Section 3.1. Moreover, the values of FTs are limited within behaviors. This choice limits the space of teleological interpretation of a behavior. In fact, semi-automatic identification of functions can be done by enumerating all possible interpretations from a given behavioral model (Kitamura et al., 2002).

Moreover, in addition to base-functions, we identified *meta-functions*. In comparison to a base-function which is a role of behavior (and device) for an operand, a meta-function is a collaborative role played by a *function* for *another function* such as ToDrive and ToProvide. For example, ToDrive means that a function supplies energy driving another function. It is the result of a teleological interpretation of causal relations among base-functions of different components. Each *base-function* has a specific *function type*, which represents causal patterns of achievement for the goals of each base-function of a

[4]P-Focus specifies not a medium (or an operand) but a flow of a medium from input port(s) to output port(s) in order to represent changes of a medium. Especially, this is for the case that a flow of a medium is branched to different ports. The example of the heat exchanger is not this case, though.

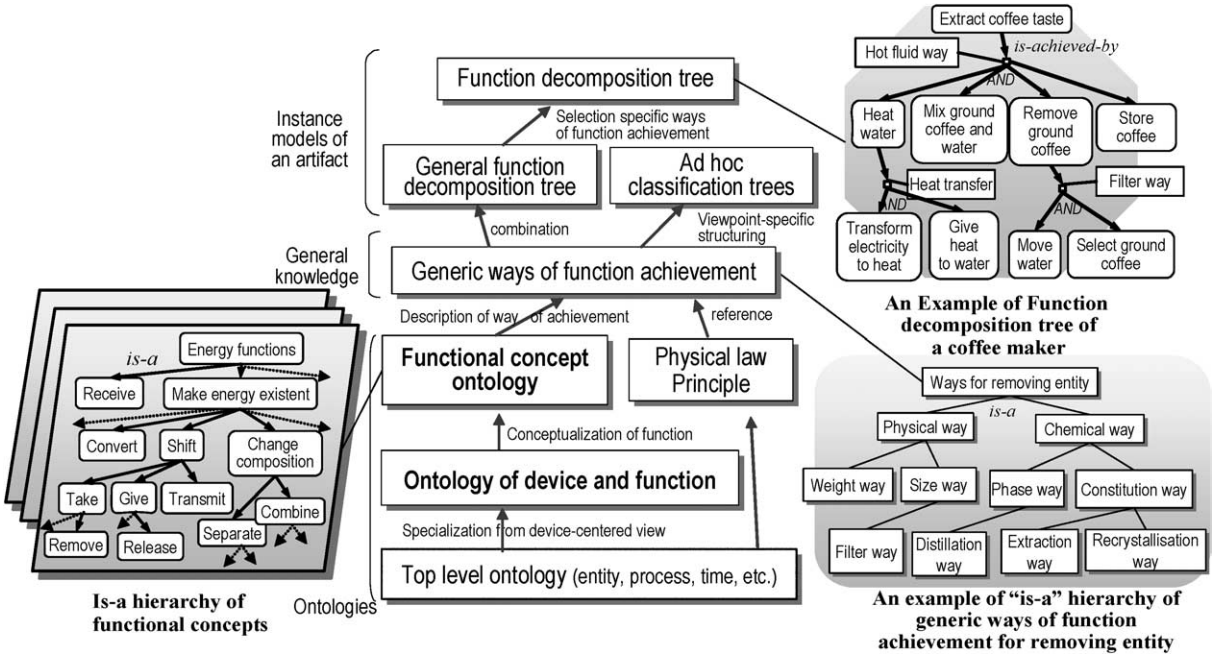


Fig. 3. Layered ontologies and functional knowledge.

component such as ToMake and ToMaintain (we redefined the ones in Keuneke (1991)). For more detail on meta-functions, see Kitamura et al. (2002).

4.2. Functional concept ontology

We developed an ontology of generic functions (called functional concept ontology) (Kitamura et al., 2002), which are sub-classes of the "function" class in the ontology of device and function. Figure 3 shows an overview of our modeling framework and a portion of the functional concept ontology.

It defines about 220 concepts in four kinds of *is-a* hierarchies with such operational definitions. For example, an energy function, "to shift energy", is defined as a behavioral constraint, i.e., as the existence of a focused-energy flow between two different mediums, with constraints which are satisfied by functional toppings as a reflection of the function context. Such energy function can be defined by the axioms inherited from its super-concept plus the following three axioms: (1) P-Focus on an inlet port and an outlet port, (2) Energy in the focused outlet port is made from energy in the focused inlet port, and (3) Mediums of the focused energies are different. *To take*, a subtype of *to shift* in the *is-a* hierarchy, is defined as FTs of *to shift* with an additional FT, P-Focus on the port of energy provider. Likewise, *to remove* is defined as a kind of *to take* with an additional FT, the energy taken is *unnecessary* as *Necessity* FT. For details, see Kitamura et al. (2002).

4.3. Function decomposition tree

On the basis of the ontologies, a *function decomposition tree* is described as a functional model of a concrete artifact. According to the extended device ontology, the knowledge authors assign *roles* to physical entities in the target world. Functions of the function decomposition tree are instances of generic

functions defined in the functional concept ontology. In the example of the coffee maker in Fig. 3, the goal function of the coffee maker is "to extract coffee taste". The whole function is decomposed into finer functions, that is, "to heat water", "to mix ground coffee and water", "to remove ground coffee" etc. The coffee maker's way of function achievement is conceptualized as "hot fluid way", whose principle is extraction by heat.

A *general function decomposition tree* includes possible alternative ways of function achievement in OR relationship for a specific goal function. It shows *design alternatives* which may be adopted or have been rejected in the previous design. It plays a crucial role in sharing design rationale.

4.4. Generic way of function achievement

The concrete *ways of function achievement* in function decomposition trees can be generalized into a generic *way of function achievement* (called functional way knowledge). Then, *ways* to achieve the same function are organized in *is-a* relations according to their principles (forming an *is-a hierarchy of ways of function achievement*). We distinguish the organization as an *is-a* hierarchy from the other derivative organizations depending on viewpoints (called an *ad hoc classification tree*). This distinction is one of the solutions for the issue in Section 3.4. Figure 3 shows a portion of the "is-a" hierarchy of generic ways of function achievement for removing entity. They are categorized into "physical ways" and "chemical ways", which are categorized into more specialized sub-classes. The filter way used in the coffee maker is sub-class of the "size way" of the "physical way".

5. Deployment in industry

The ontology and the modeling framework for functional knowledge have been deployed for over four years at the Plant and Production Systems Engineering Division of Sumitomo Electric Industries, Ltd. (hereinafter referred to as SEI) (Kitamura et al., 2004). The purpose was to share functional knowledge among engineers about the production facilities used in their daily work. After a one-year study of our framework, test use commenced in February 2001. In May, 2001, use on real problems encountered in daily work started. The targets were manufacturing facilities mainly used in semiconductor manufacturing processes including machines to slice semiconductor ingots, machines to polish wafers, a tension control system, and inspection machines.

A knowledge management software named SOFAST® (abbreviation for Sumitomo Osaka-University Function Analysis and Systematization Tool and registered trademark of SEI) has been deployed since December, 2002. It is designed to support the description of the functional decomposition trees and sharing in an intra-network. Using its client software, a user can describe function decomposition trees through a graphical user-interface and store them in its knowledge repository. Then, all users can search *ways of function achievement* in the repository to achieve the function of interest by specifying a goal function. A users' group of SOFAST software for companies was established in April, 2003.

5.1. Knowledge usages in the deployment

Figure 4 summaries some actual deployment experiences of functional knowledge. The left column enumerates the kinds of functional knowledge discussed in the previous sections. Using each knowledge form, engineers (and/or a team of engineers) can do the engineer's activities shown in the center column.

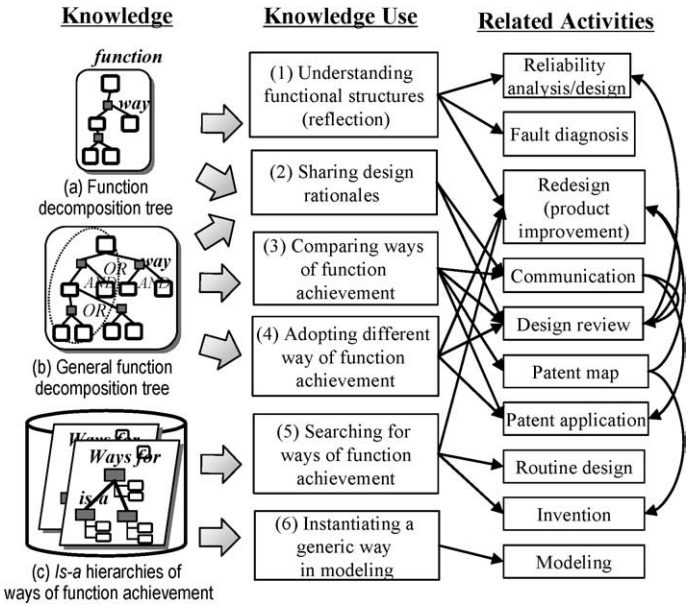


Fig. 4. Some deployment experiences of functional knowledge.

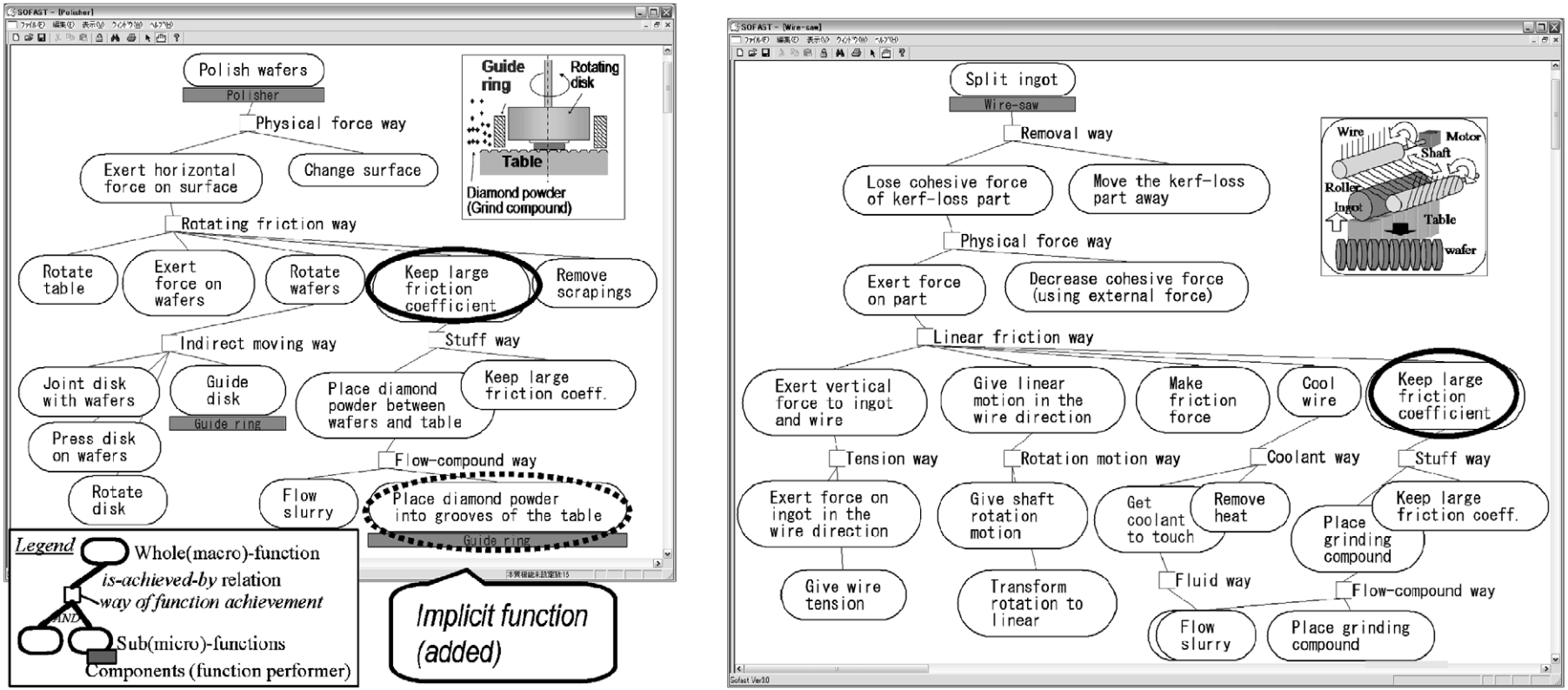
The right column shows the situations or the engineering tasks which can be facilitated by the activities. Some examples are discussed below.

One of the uses of the (general) function decomposition tree ((a) or (b) in Fig. 4) is to clarify functional knowledge, which shows design rationale and used to be implicitly possessed by each engineer, and shared it with other engineers (Usage (2) in Fig. 4). The experiential evaluation by Sumitomo's engineers was unanimously positive. The chosen case study was the development of design-review documents, where a design team checks a design and explores possible alternatives. In replacement of a comparative table with a text, the engineers started to use the (general) function decomposition trees for design-review documents. After adopting our framework, the number of times the design reviews had to be done was successfully reduced to one third. This is because the function decomposition tree shows how to achieve the goal function as one of design requirements and then facilitates extensive discussion with other team members. Especially, the general function decomposition tree has a strong effect on design review in order to compare alternative *ways* of achieving functions for each (sub) function (Usage (3) in Fig. 4). It shows their features in comparison, and reasons for adopting a specific way, or not, in a single glance. Such information is crucial in design review.

Writing a function decomposition tree according to the methodology gives designers the chance to reflect on positive stimuli, which leads them to an in-depth understanding of the equipment (Usage (1) in Fig. 4). Such a deep understanding of the equipment contributes to redesigning and solving problems with it.

For example, an engineer was not able to reduce the time a machine requires to polish semiconductor wafers after four months of investigation by adjusting the known working parameters. He reported the function decomposition tree shown in Fig. 5(a), which is a screen snapshot of the SOFAST software[5].

[5]The current version of SOFAST does not provide sufficient support for English. These snapshots are intended to show the functional decomposition trees for explanation and to provide rough images of SOFAST.



(a) (b)

Fig. 5. (a) Function decomposition tree of a polisher which was described for its improvement; (b) function decomposition tree of a wire-saw which was referred to.

He understood the guide ring as having only one function, that is, to guide the movement of the rotating disk. The rotating disk freely moves inside the guide ring for polishing the wafer. Thus, he was not aware of another implicit function, "to place diamond powder into grooves of the table" (i.e., the function marked with dotted circle was missing). He recognized the missing function when looking at the wire-saw function decomposition shown in Fig. 5(b). Although these two devices have different main functions and the wire-saw knowledge had been described by another engineer, he found the shared function "to keep a large friction coefficient" (marked with circles in Figs 5(a) and 5(b)) and its subfunction "to place grinding compound" in the wire-saw model. As a result, he became aware of the missing function in the polisher model and its parameters for placing more diamond powder (that is, the width of the guide ring) to obtain a high friction coefficient. Eventually, he reduced the necessary time to 76%, which was better than the initial goal. This improvement was achieved within three weeks. This example shows that functional knowledge tends to be implicit and awareness of such functionality gives engineers good stimuli for improvement. Moreover, reuse of functional knowledge between different facilities contributes providing the stimuli.

Comparing design candidates as different ways to achieve functions (Usage (3) in Fig. 4 of the general function decomposition tree) contributes to patent analysis and patent applications as well as to design review mentioned above. In communications between engineers and patent attorneys in applying for a new patent, it is difficult to determine the product's originality and to make appropriate claims. When the general function decomposition tree has been adopted as regular document format for patent application, the period was reduced to just one week from three or four weeks. The patent claims were increased and doubled in some cases, since the attorneys found extra differences with other patents by checking at each level of function decomposition. The same benefit was found by another company in the users' group.

Generic knowledge about ways of function achievement ((c) in Fig. 4) helps designers search ways to achieve a function and/or alternatives in an existing product. In the deployment, a novice engineer developed an inspection machine in three days by systematically consulting generic ways of shedding light in the knowledge repository of SOFAST. Such development usually requires experts two weeks. Note that the SOFAST search for possible *ways of function achievement* for a specific goal-function starts from concrete *ways* used in machines, and not from generic *ways* in *is-a* hierarchies. Moreover, discrimination of *is-a* relations from *ways of function achievement* has helped engineers avoid a great deal of possible confusion.

5.2. *Effects of the ontologies*

One of the effects of the functional ontologies is to give prescriptive constraints for contents of functional knowledge. Because functional knowledge is intrinsically subjective rather than objective, without a guideline, novice modelers would be puzzled in describing functional models. Especially, the extended device ontology provides users with hints on interpreting how a device works consistently. It provides concepts for assigning "roles" to each object in the target world. For the wire-saw example discussed in Section 3.3, the wire can be considered as an *agent* (exerting force on ingots), an *operand* (moved by the roller) or a *conduit* (transmitting tension) depending on its location. According to semantic constraints in the extended device ontology, a possible way to consistently assign roles is to decompose the wire into two parts, a working wire playing an *agent role* and a transmitting wire playing both a *medium* role and a *conduit* role.

The explicit modeling of "ways of function achievement" also helps modelers to eliminate the confusion between "what to achieve" and "how to achieve it". A clear distinction between a general-specific

hierarchy (*is-a* relations) and a whole-part hierarchy (*is-achieved-by* relations) helps knowledge authors to have consistent descriptions of function decomposition trees and *is-a* hierarchies of *ways of function achievement*. This avoids the confusion between the two, which has often occurred as discussed in Sections 2 and 3.4. For example, the "to weld" function discussed in Section 2 can be described as a *fusion way* of the *joining function*. The fusion way has specific characteristics of the output, namely that the operands are fused and they are hard to be separated. Although a functional concept "to join" loses some amount of information with respect to "to weld", what it loses goes to the characteristics of the fusion way. In sum, functional concepts are successfully made very generic without any loss of information.

Furthermore, functional ontologies provide an appropriate level of abstraction in order to recognize "commonalities" between products for sharing knowledge over different products. Usually, the engineering knowledge is described in a product-specific manner, which restricts the applicability of knowledge to a specific product. Thus, engineers have difficulty to find related knowledge in different products or domains. The concept of function itself is a solution, since a function is intrinsically abstract and independent of its realization (e.g., structure and material). Nevertheless, many functions in practice imply the way of function achievement such as "welding", which is a kind of dependence on realization. It fails to recognize the commonality between artifacts. In our framework, on the basis of the concept of the way of function achievement, we established an ontology of functional concepts, which enables the computer systems to find more artifacts to match with a specific artifact.

Lastly, our ontology-based modeling framework provides a knowledge medium to externalize engineers' understanding that used to be implicit. In the SEI deployment, engineers said that writing functional models of their own equipment gives them chances to reflect and obtain good stimuli, which leads them to an in-depth understanding of the equipment. The micro-macro hierarchy of the function decomposition tree enables the designer to systematically explore possible alternatives (for conceptual design) and/or possible problem sources (for problem solving) for each function. For example, fault tree analysis (FTA) for trouble shooting tends to make it difficult to enumerate all possible causes without a clear understanding of the function structure of the target device.

5.3. Lessons learned

Although the deployment was successful, we faced some difficulties. This sub-section summaries the lessons learned, i.e., the main issues emerged and some difficulties.

The first issue we had to face was how to give a driving force to make engineers use new (unfamiliar) technologies, i.e., the ontology-based modeling framework and the SOFAST software. Generally, engineers are very busy and have no strong motivation to use new technologies in their daily work. Especially, in general situations of knowledge management projects, knowledge authors have no effective motivation to write their own knowledge and share it with others.

In the deployment, SEI's managers established a regulation and a reward system for using the modeling framework. A department regulation enforced engineers to use the general function decomposition tree as an official standard format for design review documents. This regulation added no extra effort for engineers, because the function decomposition tree was adopted instead of conventional documents in a table form. This fact had a good effect for engineers from the viewpoint of the modeling cost. On the other hand, the rewards were given as a part of the company's management system for workers evaluation. Both organizational incentives successfully gave engineers a chance to write a function decomposition tree at least as a test use.

In addition to such incentives, engineers' motivation came from the direct benefits of writing functional models. Such motivation is much different from "no effective motivation" in the general situation

of knowledge management projects mentioned above. In the deployment, the engineers said that they obtained benefits from writing functional models of their own equipment, since it gave them the chance to reflect and obtain good stimuli, which lead them to investigate possibilities in design or diagnosis systematically and exhaustively as discussed in Section 5.2. Moreover, sharing an initial successful use of a functional decomposition tree gave effective triggers to use by other engineers. The fact that we got a successful test-use in the early phase of the deployment played a crucial role in promoting our technology to other departments and other companies.

The second issue is how engineers learn the modeling framework. The ontological modeling framework needs training for writing functional models that are compliant with functional ontologies. Using the SOFAST software is easy to learn, but writing function decomposition tree is not easy. Some engineers were puzzled out, or wrote functional decomposition models that were not compliant with the ontologies and thus not reusable for other products. In the deployment, the SOFAST users' group held many practicing sessions for writing functional models using real examples submitted from member-companies.

Moreover, it turned out that it was not easy for engineers to select appropriate functional concepts according to ontological definitions. People felt difficulty learning definitions of the functional concepts. One of the reasons was that we gave theoretically-sound names to the concepts, which were sometimes unfamiliar to engineers. Considering engineers' preference, it is useful using terms belonging to a domain-specific vocabulary familiar to them. We never claimed completeness of concepts in our functional concept ontology due to its nature and understand the necessity of extending it.

These difficulties found in the deployment gave us a motivation for the following twofold extensions of our ontological framework for easier use. One concerns the treatment of lexical terms for representing functional concepts in order to reduce the difficulty in selection of functional concepts. The other is the establishment of ontological guidelines in order to make ontological commitment easier.

6. Extension

In order to resolve some difficulties discussed in the previous section, we had developed a second version of SOFAST (the version number is 3. hereafter SOFAST V3). In this section, we discuss two extensions of SOFAST.

6.1. Lexical layer

The deployment experience shows the importance of flexible lexical terms for representing functional concepts. It is useful to have a domain-specific vocabulary with different terms for the same concept. Thus, SOFAST V3 supports multiple layers of functional-terms as shown in Fig. 6. It consists of four layers, i.e., an ontology layer, a concept layer, a lexical layer, and a domain-specific layer. The *ontology layer* is for the functional concept ontology, which defines functional concepts with an explicit relationship with behaviors. It is organized in a rather deep (from three to six levels) *is-a* hierarchy for each kind of target operand. Each functional concept has a term to represent the concept, which is just a label for human readability. We do not claim the appropriateness of the labels themselves.

The *concept layer* is a simplified version of the organization of functional concepts in the ontology layer, which is a single three-level hierarchy. Some intermediate concepts in the ontology layer are omitted in the conceptual layer. It makes engineers' understanding of functional concepts' organization easier. The concept layer is implemented in SOFAST V3 as *essential functional concepts*. The mapping

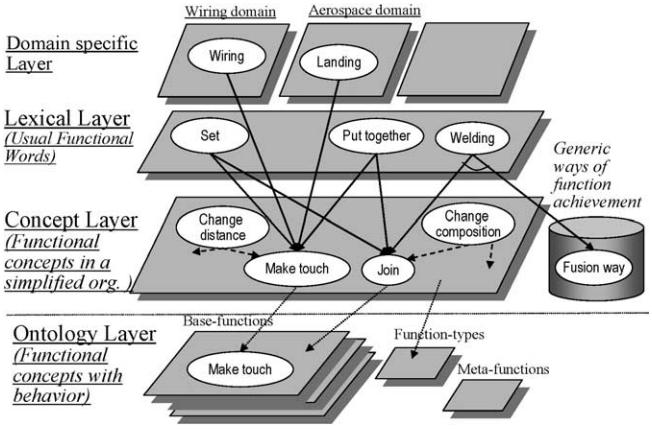


Fig. 6. Multiple layers of functional terms with examples.

between the concept layer and the ontology layer was made by the authors as a part of application development.

The *lexical layer* includes *usual functional words,* which are verbs for representing functions appearing in daily work. The usual functional terms have been prepared beforehand in collaboration with companies in the users' group. The domain-specific layer has some vocabulary sets specific to domains or companies.

Such *usual functional words* are associated with *essential functional concepts*. A usual functional word can represent some essential functional concepts and vise versa. For example, a usual functional word "to put two objects together" can imply either of (at least) the following two functional concepts:

(1) The two objects which are independent of each other become fixed together in a cohesive manner. This is a sub-concept of "to change composition of operands". In the concept layer, this concept is denoted by "to join".
(2) The distance between two objects changes from a positive number to zero. This is a sub-concept of "to change distance". In the concept layer, this concept is denoted by "to make operands touch".

Thus, the usual functional word "to put together" has the mapping relations to the functional concepts "to join" and "make touch". On the other hand, there are other usual functional words for these functional concepts. For example, "to make touch" can be referred to as "to set" as well.

Some usual function words imply not only functions but also specific ways of function achievement. For these words, the mapping shows a decomposition relation. For example, a term "to weld" can be decomposed into the "to join" functional concept and the fusion way.

The multi-layer functional terms are used in selecting a label for a function node in SOFAST V3. Users can select a function using either essential functional concepts or usual functional words. When a user selects a usual functional word which is associated with some essential functional concepts, the user has to select an essential functional concept from these candidates. Thus, a function node in the function decomposition tree has both a usual functional word and an essential functional concept. In the diagrammatic representation of the function decomposition tree in SOFAST V3, the usual functional word is used. When a user searches instances of functions in functional decomposition trees, the user can search using essential functional concepts. Thus, users can search functions independently of lexical (superficial) representation of the function.

6.2. Ontological modelling guidelines

In order to help easier commitment to the ontologies, the authors had established stepwise guidelines for describing functional knowledge shown in Table 1 (Kitamura & Mizoguchi, 2004b). They show ontological constraints for contents of models in the form of a checklist in natural language. A model-author can check a function decomposition tree using the guidelines and then can modify it if necessary. The guidelines are categorized into three groups, i.e., Group F: guidelines about functions and behavior, Group S: guidelines about relations between method-functions (i.e., sibling functions at a level of decomposition), and Group A: guidelines about "is-achieved-by" relations (between goal and method functions. i.e., decomposition relations) and ways of function achievement.

Figure 7 shows an example of modification process of the function decomposition tree of the wire-saw which is shown in Fig. 5(b). Figure 7(a) shows the initial model and (b) the revised one. In the example, the whole function "to slice" in Fig. 7(a) is modified into "to split" shown in Fig. 7(b), because "to slice" implies "how to split" and provides specific information about the thinness of the split part.

Table 1
Guidelines for function decomposition trees

F. About functions and behaviors	
F1.	A function represents "what to achieve" only and does not imply "how to achieve".
F1-1.	A device is a black-box. The inside is not shown at a level.
F2.	A function represents (a teleological interpretation of) changes in physical things within the system boundary.
F2-1.	Do not describe the designer's activities.
F2-2.	Distinguish product's functions and manufacturing processes.
F2-3.	Determine a system boundary with a pre- and post-process.
F3.	The agent of a function should be a "device" in the physical world.
F3-1.	A human operator can be regarded as a "device".
F3-2.	Designers and operators (workers) in manufacturing processes should be distinguished.
F3-3.	Sizes of devices decrease in function decomposition.
F3-4.	A device can be virtual and/or dynamic.
F4.	Decompose functions which imply a kind of operands and/or degrees of results for functions. Such implications are represented as attributes of *ways of function achievement*
S: About relations between sub-functions	
S1.	Identify states of operands that flow through sub-functions.
S2.	Time passes along these relations.
S3.	Roles of things as operands should not be changed in a series of sub-functions.
A: About "is-achieved-by" relations and ways of function achievement	
A1.	The "is-achieve-by" relation represents a kind of aggregation
A1-1.	The total changes in sub-functions should correspond to changes in the whole function.
A1-2.	This relation does not imply a time interval.
A1-3.	This relation is not an "is-a" relation.
A2.	A sub-function should explicitly contribute to a macro-function.
A2-1.	Explicate implicit sub-functions.
A3.	The *way of function achievement* represents a single principle.
A3-1.	Decompose compound principles.
A3-2.	Distinguish a *way* from other *ways* at the principle level.
A3-3.	If possible, conceptualize neither a tool nor a kind of an operand but a principle.
A3-4.	A way should refer to a direct macro-function.
A4.	Distinguish supplementary functions from essential functions.

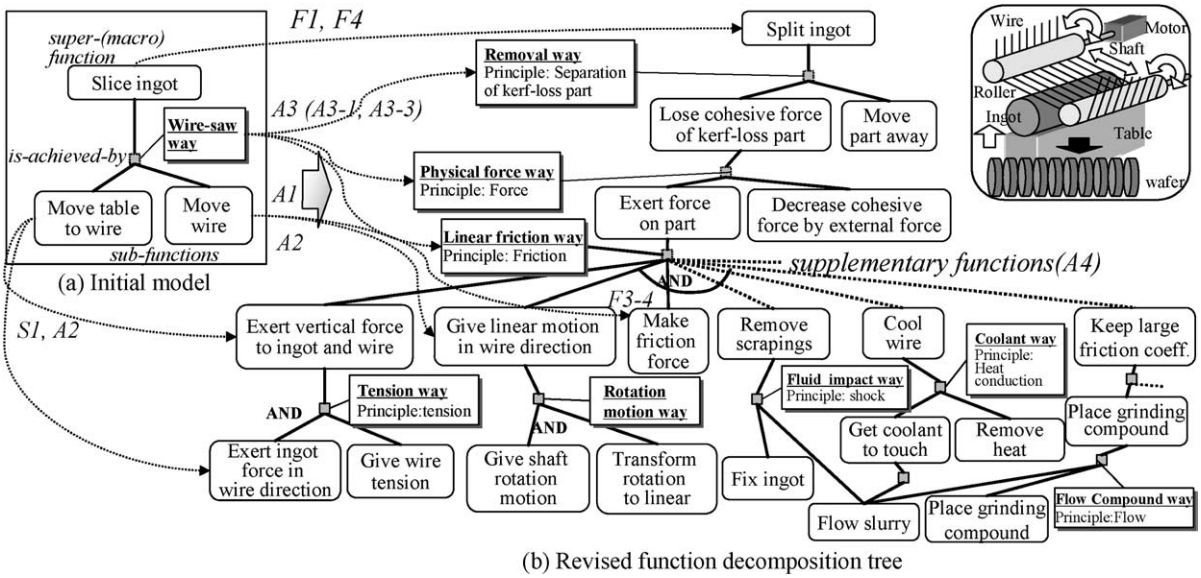


Fig. 7. A modification of a function decomposition tree of a wire-saw for slicing ingots (portion).

The former information is regarded as the way of function achievement. Thus, the functional term "to slice" does not follow the guideline F1 in Table 1. The goal of slicing here can be considered to be "to split apart the target operand (i.e. ingot)". It makes it possible to select other ways instead of "slicing" in the design. In reality, slicing with wire is not a simple way of function achievement but a composite as will be discussed later. The latter information (i.e., thinness), on the other hand, is regarded as the quantitative degree of a function. Thus, the function term "to slice" does not follow the guideline F4. Each way of function achievement has specific value of attributes like it. Then, such information can be used as conditions to select the way from all available ways of function achievement.

As we can see in Fig. 7(a), one might describe "to move table to wire" and "to move wire" as sub-functions. However, against A2 in Table 1, the reason why these two sub(method)-functions can perform the whole (goal) function is not clear. Moreover, against S1 in Table 1, it is unclear which operands flow between the two sub-functions. One reason is that there is a missing function, "to exert vertical force to ingot and wire". The original sub-function "to move table to wire" contributes to the vertical-force sub-function.

The *wire-saw way* in Fig. 7(a) does not involve a single *way* against A3 but a composite of three *ways*, i.e., the removal way of splitting, the physical force way of losing cohesive force of a part (kerf loss, i.e., the part lost by cutting), and the linear friction way of exerting force. Splitting is achieved by two sub-functions; losing the cohesive force of the kerf-loss and moving it away. This *way* to achieve the function is conceptualized as the removal way based on separating the kerf loss part.

Currently, the guidelines are only for human comprehension. Engineers themselves have to check their models according to the guidelines. Automatic checking of violations in the functional models based on the ontological guidelines is being investigated. Their definitions are structured with slots and constraints and include axioms as a result of deep insights into the behaviors and functions in physical systems. Such formal definitions can be used to automatically check the models.

7. Related work and discussion

7.1. Definitions and categories of function

Our ontology of device and function discussed in Section 4 defines the concept of functionality strictly from the device-centered viewpoint. Such strict definition is intended to prescribe guidelines to functional modeling. In the literature, there are many definitions of function with different meaning. Figure 8 shows some categories of function, which are intended to show differences between our definition and some of other definitions. Note that Fig. 8 shows an "is-a" hierarchy of categories of functions only for readability, because some distinctions are independent of each other.

Chandrasekaran & Josephson (2000) discuss a kind of function called *environment function* as an effect on environment (the surrounding world of the device). Some researchers distinguish *purpose* from function (Chitaro et al., 1993; Lind, 1994; Hubka & Eder, 1988, 2001), where the purpose represents human-intended goal. Such concepts are different from our definition of function in the scope of the target operand to be changed, i.e., they include changes outside of the system boundary, especially, those related to *users* or *user actions* (here we call an *environmental function* based on the categorization shown in Fig. 8(a)). On the other hand, the function discussed in Section 4 represents changes of entities (behaviors) within the system boundary (here we call *device function*). For example, an electric fan performs moving-air function as a *device function* and cooling function for human body as an *environmental function*, where the cool-down effect by wind is on human body and thus outside of the system boundary.

This cooling *environmental function* means physical changes of the system (called *physical environmental function*), while an *interpretational function* sets up one of necessary conditions of human's cognitive interpretation as shown in Fig. 8(b). For example, a clock has "to rotate hands (in the specific and constant rate)" as a *device function* and "to inform time" as *an interpretational function*, which requires human's cognitive interpretation. Similar concepts of functions can be found in the literature. Rosenman & Gero (1998) investigate *purpose* in *socio-cultural environment*. The situated FBS framework treats change of requirements (Gero & Kannengiesser, 2002). In our collaborative work with the Delft University of Technology, we are extending our framework to include user actions as well (van der Vegte et al., 2004). The affordance-based design has been investigated in (Maier & Fadel, 2003).

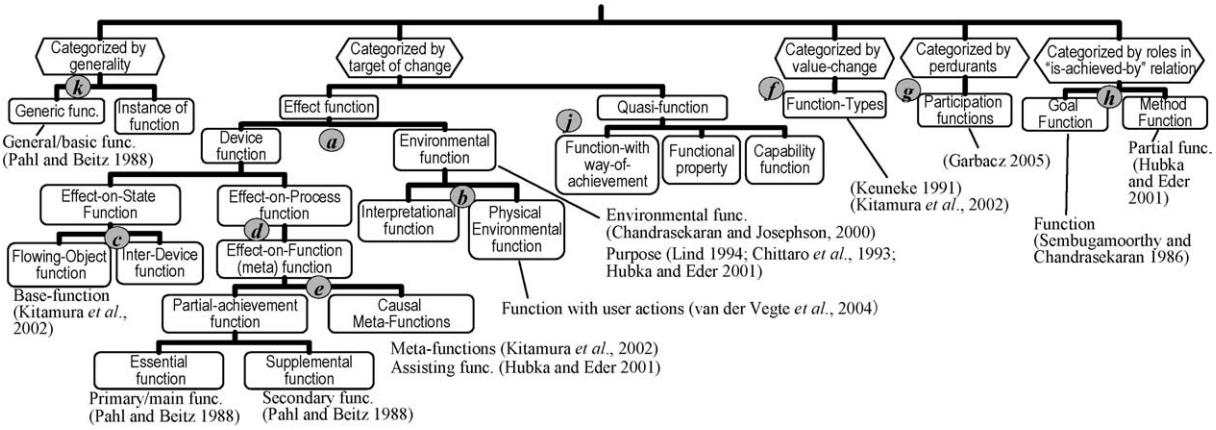


Fig. 8. Some other definitions and categories of function in the literature.

The *base-function* discussed in Section 4 refers to temporal changes of physical attributes of objects which flow through the device (called *flowing object* function as shown in Fig. 8(c)). It can be generalized into *effect-on-state function* which means temporal changes of physical attributes. The effect-on-state function has another kind, that is, *inter-device* function which refers to changes of another device (called B-3 behavior in (Kitamura & Mizoguchi, 2004a)). Its example is a rod's function "to push cam". The cam is another device, which is not considered as objects flowing through the rod.

On the other hand, the *effect-on-process function* represents an effect on a process or its changes. Behavior as basis of function can be regarded as a kind of a process. Thus, as a subtype of the effect-on-process function as shown in Fig. 8(d), *effect-on-function function* (we can call meta-function) represents a role of a function for another function. It includes *partial-achievement function* and *causal-meta function* as shown in Fig. 8(e). The former is performed by a *method function* for a *goal function* in the *is-achieved-by* relation. The achievement function can be categorized into the essential function and the supplemental function. Distinction of primary function and secondary function (Pahl & Beitz, 1988) is similar to this. The latter, causal-meta function, represents a role for another method function and is called a *meta-function* in Section 4.1 and Kitamura et al. (2002). Hubka & Eder (1988, 2001) categorize some types as assisting function.

The function-types have been identified by Keuneke (1991) based on patterns of value change as shown in Fig. 8(f). We redefined it as categorization of changes of values (Kitamura et al., 2002) as discussed in Section 4.1. Garbacz (2005) defines *participation functions* according to categories of perdurants (i.e., occurrent in Fig. 2. This is shown in Fig. 8(g)). They are "achieve", "accomplish", "maintain" and "process", which correspond to achievement, accomplishment, state and process, respectively.

In the context of the "is-achieved-by" relation, we can recognize a role of function, i.e., goal-function and method-function as shown in Fig. 8(h). Function defined in (Sembugamoorthy & Chandrasekaran, 1986) is related with the former as discussed in Section 3. The latter is called partial function (Hubka & Eder, 1988). In German systematic design methodology, the generic class of function is called general function or basic function (Pahl & Beitz, 1988).

We recognize the following three kinds of *quasi-functions* as shown in Fig. 8(j). Although the authors do not consider them as kinds of functions, it is found that a quasi-function is occasionally confused with a function. Firstly, a *function-with-way-of-achievement* implies a specific way of function achievement as well as a function. Its examples include washing, shearing, adhering (e.g., glue adheres A to B), "transportation by sea" (Hubka & Eder 1988), "link" (Hirtz et al., 2002) as well as welding mentioned in Section 2. Because meaning of this type of function is impure, we regard this quasi-function.

Secondly, a *functional property*[6] represents the fact that an artifact (usually a material) has a specific attribute-value which directly causes functionality. This is found in material science domain where a material whose function is dependent on its electronic, optical or magnetic property is called a functional material (EPSRC, 2005). For example, if the electrical conductivity of a material is high (i.e., it has a high-conductivity property), the material can perform the "transmit electricity" function. There is a direct relationship between the high-conductivity property and the transmitting function. Lastly, a *capability function* represents the fact that an entity can perform an activity which has no effect on others. For example, people say that "a human has a walking function". Hubka & Eder (1988) also define a function as a capability for achieving a goal. However, their definition implies effects on operands in contrast with the capability function here.

[6]The term "functional" here is intended to represent neither mathematical dependence relation nor attributes of function but function-oriented property, though attributes of function include (not only) functional properties. Functional property is used as an antonym of mechanical or structural property.

7.2. Generic tasks and the upper-level concepts

Our functional ontology is different from "task" knowledge of designing or diagnosing, which is an activity of human or automated problem-solvers. If one ignores the difference between domain and task, the generic tasks and the generic methods (PSMs) in the task ontology research (e.g., Schreiber et al., 2000) are similar to our generic functions (as the antonym of 'instance of function' as shown in Fig. 8(k)) and to our generic ways of function achievement, respectively. We focus on structuring knowledge about how to achieve functions (activities in domain world). We conceptualize the principle behind the sequence of activities (called method in both researches) as the way of function achievement. It helps us organizing them in *is-a* hierarchies, while PSMs for a specific task are usually not organized well. Moreover, we distinguish function at the teleological level from behaviors at the objective level.

Behavior of artifacts is a kind of "process" by which we intuitively mean a sequence of state changes over time. We concentrate on physical processes representing temporal changes of physical quantities as we discussed in Section 4 and in this section. On the notion of generic "process", extensive research has been done such as the process specification language (PSL) (ISO, 2003) for "activities" and their temporal relationships, formal ontologies for processes (e.g., Sowa, 1995), and the MIT process handbook for business activities (Herman & Malone, 2003) whose taxonomy for business activities includes "activities-with-way" such as "buy in a store" similarly to "welding" in Section 2.

In Fig. 2, we show some upper-level types such as 'state', though we aim not at a new proposal of the upper-level types but at clarification of our definition of the function-related types. Many upper-level ontologies include similar types. For example, in comparison with DOLCE (Masolo et al., 2003), our types; *continuant, occurrent, physical-entity, stative (occurrent)* and *active (occurrent)* in Fig. 2 roughly correspond to *endurant, perdurant, non-agentive physical entity, state* and *process* in DOLCE, respectively.

Our definition of function is based on the notation of role concept (Kozaki et al., 2002; Sunagawa et al., 2006). Much research has been conducted on representation of roles; e.g., (Fan et al., 2001; Gangemi & Mika, 2003; Masolo et al., 2004, 2005; Sowa, 1995). Our analysis of function as role discussed in Section 3 follows the role's characteristics discussed in these papers. Both Masolo et al. and we introduce a context to define a role. The difference is that their context is a description of a situation on the basis of D&S theory (Gangemi & Mika, 2003), but ours is a normal concept defined in a base ontology like DOLCE. In this paper, we defined two types of *contexts* for functions. Although we have our own ontology of descriptions (representations in our terminology) and it is interesting to discuss how this is different from D&S, this is beyond the scope of this paper.

The exclusive features of our theory of roles include a clear distinction between instantiating a role and playing the actions of a role and hence between the instance of a role and the existence of the role playing thing (*role-holder* in our terminology). The 'qua-individual' in Masolo et al. (2005) is similar to an instance of a *role-holder*. We conceptualize both a class of a role concept and a class-equivalent of a role-holder. Such distinction enables us to represent an unplayed role (i.e., an instance of role without instance of a role holder). For example, when a vacancy on a teacher post arises, there is no instance of the *teacher* role-holder but an instance of the *teacher role* which has properties such as subject. See details in Sunagawa et al. (2006).

7.3. Ways of function achievement

Similarly to the *ways of function achievement*, a feature of function decomposition can also be found as a "means" in Malmqvist (1997), Bracewell & Wallace (2001), Wilhelms (2003). We defined *is-a*

relations between conceptualized generic *ways of function achievement*, and investigated how to organize them.

The generic way of function achievement aims at its generality by pointing out partial (and abstract) information on structure and behavior. The related notions in the literature, the design prototypes (Gero, 1990) and the FBS modeling framework (Umeda et al., 1996), include structural decomposition and physical features, respectively. In IDEAL (Bhatta & Goel, 1997), generic teleological mechanisms (GTM) are used (modified) to design different contexts based on analogies. In our approach, based on a limited set of functional concepts, designers can explore explicit *is-a* hierarchies of *ways of function achievement*.

TRIZ (TIPS) theory provides some patterns (or strategies) for inventions based on the contradiction between two physical quantities (Sushkov et al., 1995). We did not concentrate on design strategies but on modelling schema. TRIZ theory also concentrates on physical principles (effects), while we established a clear relationship between physical principles and functional structures.

7.4. Limitations

Besides production systems, the ontologies presented here have been applied to modelling a power plant (Kitamura et al., 2002), an oil refinery plant, a chemical plant, a washing machine, a printing device, and various manufacturing processes. The models have taken into account changes in thermal energy, flow rate, and ingredients of fluids, including force and motion of operands. The current functional concept ontology can describe simple mechanical products, although it does not cover static force balancing and complex mechanical phenomena based on the shape of operands. The modeling framework currently cannot cope with human mental processes, body movements (so-called therblig in Industrial Engineering), business processes, or software processes.

8. Concluding remarks

An ontology of functionality of artifacts and an extension of the ontology-based modeling methodology based on deployment experience of such ontology have been discussed. The role of ontologies is to provide semantic guidelines to capture the target world consistently and a controlled vocabulary for representation.

The authors and their colleagues are currently investigating more simplified functional models expressed as meta-data for web documents (Kitamura et al., 2006). In this framework, a knowledge author can choose the level of description, from just a keyword representing the whole function of the device to a full functional model as discussed in this paper. Such functional knowledge associated with web documents in natural language will reduce the cost of modeling according to company's demand.

Moreover, aiming at interoperability between functional knowledge and failure knowledge, the authors and colleagues are extending the framework to cope with unintended behaviors such as faults (Koji et al., 2005).

Acknowledgements

The authors would like to thank Kouji Kozaki, Munehiko Sasajima, Eiichi Sunagawa, Shinya Tarumi, Naoya Washio for their contributions to this work. Special thanks go to Dr. Masayoshi Fuse, Mr.

Masakazu Kashiwase, Mr. Shuji Shinoki and the engineers in the Plant and Production Systems Engineering Division of Sumitomo Electric Industries, Ltd. for their cooperation with the deployment. The authors are grateful to the two reviewers: Stefano Borgo and Tania Tudorache for their valuable comments. Special thanks also go to Nicola Guarino for his kind help in improving this paper.

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