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AN ONTOLOGY OF CLASSIFICATION CRITERIA FOR FUNCTIONAL TAXONOMIES

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ABSTRACT

In order to facilitate sharing of functional models, some functional taxonomies each of which provides a set of verbs for representing generic functions (called functional terms here) have been developed. Their examples include some sets of generally valid functions in the book written by Pahl and Beitz, Functional Basis (FB) developed by Hirtz et al. and FOCUS/Tx developed by the authors of this paper. The issue addressed in this paper is the implicitness of the criteria of classification of functional terms in those taxonomies and thus unclearness of their definitions. This paper proposes an ontology of logical criteria for classification of functional terms (called FOCUS/View). Using the classes defined in FOCUS/View, the classification criteria of a functional taxonomy can be explicitly represented. These classes have been conceptualized based on deep investigation on FB and FOCUS/Tx. The benefits of the proposed FOCUS/View ontology include: (1) users of a taxonomy can easily understand differences of similar terms and select an appropriate term out of them, (2) a developer of a taxonomy can check its logical classification structure and then improve its logical clearness, and (3) we can compare different taxonomies and establish more reliable mappings between their terms for interoperability of functional models. In this paper, as a demonstration of the benefit (1), the classification criteria of FB, FOCUS/Tx, Krumhauer's and Roth's generally valid functions are explicitly presented using FOCUS/View. As a demonstration of the benefit (2), some logically problematic classification structures of FB and the Krumhauer's functions are discussed and modified for the logical clearness. For the benefit (3), this paper demonstrates the mappings between FB and FOCUS/Tx and a semantic interoperable document search system based on these mappings.

KEYWORDS

Functional representation, ontology, functional design, design knowledge modeling

1. INTRODUCTION

Functionality is one of the key aspects of knowledge about artifacts. Thus, a functional model, i.e., a product model from the viewpoint of functionality, plays a crucial role in the conceptual design and in other engineering activities. Much research on the functional models such as [1-11] has been carried out to date. A function of a component or a system in a functional model is typically expressed as a pair of an active verb and its (grammatical) object like in Value Engineering [1]. We here concentrate on such active verbs representing functions (called *functional terms* hereinafter).

Sharing such functional models in engineering organizations facilitates engineering activities. One of the important approaches for this is to establish a taxonomy of general functional terms and to use it for representing functions in the functional models. Such a taxonomy provides a shared and controlled vocabulary for functional models and makes it easier to search them using the functional terms in the taxonomy.

Thus, some functional taxonomies have been proposed to date [4][5][9][12][13][14]. For example, the book [5] by Pahl and Beitz shows some taxonomies of *generally valid functions* in the German design methodology, which have been proposed by Krumhauer, Roth and others independently. In US, Reconciled Functional Basis in the NIST Design Repository Project has been established [9] as a reconciliation of the original Functional Basis [13] and other taxonomy [14]. This consists of a taxonomy of function (verb) and that of flow. We concentrate on the taxonomy of function as a functional taxonomy and call it FB in this paper.

The authors have been involved in the research on functionality based on Ontological Engineering [15][16][17] and have established a suite of functional ontologies named

FOCUS[1] [18]-[25]. The framework has been successfully deployed in industry [20]. The effects of sharing functional models in engineering organizations mentioned above have been confirmed in this deployment. As a part of this suite of ontologies, an ontology of functional concepts (named FOCUS/Tx) defines functional terms and can be used as a functional taxonomy for functional models.

The functional terms in the functional taxonomies are defined and classified according to different criteria. The issue addressed here is such criteria for classification are implicit in the taxonomies. In many taxonomies, the terms are defined in natural language and then the criteria are, in many cases, implicit. Thus, such definitions are sometimes ambiguous and it is difficult to distinguish similar terms. For instance, 'extract' and 'remove' in FB [9] are defined as "draw, or forcibly pull out, a flow" and "to take away a part of a flow from its prefix place", respectively. It might be difficult to catch exact difference between them and to select an appropriate one for a device. In fact, Garbacz points out some problems of the classification of FB such as lack of principle of classification and non-exhaustiveness from logical and ontological viewpoints [26].

The goal of this research here is to propose an ontology for classification of functional terms (named FOCUS/View), which defines common criteria used in classification in functional taxonomies. For example, FOCUS/View defines "the sameness of kinds of operands (target objects)" as a classification criterion. As a result of our investigation on FB's definitions, we reveal that the terms 'extract' and 'remove' in FB seem to be distinguished based on this criterion. The term 'extract' is intended to use for the case where a flow is separated from the different kind of flow(s) and the term 'remove' is intended to use for the case where a flow is separated from the same kind of flow. In this way, the meaning of functional terms in a functional taxonomy can be explicated using FOCUS/View.

The main aims and benefits of FOCUS/View include:

a) From the scientific point of view, to clarify how to classify functional terms in a comprehensive and logical way;
b) For users of a taxonomy, to facilitate understanding of the meaning of functional terms in the functional taxonomy and selecting an appropriate term out of similar terms;
c) For users of multiple taxonomies, to facilitate comparison of functional terms in those taxonomies;
d) For a developer of a functional taxonomy, to help him/her check the logical structure of the classification and to facilitate improvement of its logical clearness;
e) For researchers of functional taxonomies, to help them establish clearer and more reliable mappings between functional taxonomies, and
f) For engineers intending to share functional knowledge, to enable them to access documents annotated with either of functional taxonomies using a semantic document search system based on those mappings.

In this research, for establishing FOCUS/View, we have conducted the research following the four steps shown below:

1 To investigate the definitions of functional terms in FB and FOCUS/Tx as examples of functional terms,
2 To reveal the criteria of classification of functional terms in these taxonomies,
3 To integrate those criteria and organize them as an ontology, and
4 To apply the organized criteria for some taxonomies for suggesting their generality.

In this paper, we firstly show an overview of the framework with an example in Section 2. Section 3 presents the contents of FOCUS/View (as a result of the step 3 above) with its base-model for capturing functions. In Section 4, as demonstrations of how to use the ontology and of its benefits (a), (b) and (d) shown above, the classification criteria of some existing functional taxonomies (i.e., FB [9], FOCUS/Tx [24], Krumhauer's generally valid functions [5], and Roth's ones [5]) are presented using FOCUS/View. As a result of this analysis, some logically problematic structures of classification in FB and the Krumhauer's one and their modification are discussed. These are examples of the benefit (d). Note that this is just a demonstration of the benefit of clarifying classification criteria. We intend neither to evaluate these taxonomies nor to criticize them.

Aiming at a demonstration of the benefits (c), (e) and (f), Section 5 presents mappings between functional terms of FB and those of FOCUS/Tx and a semantic document search system based on these mappings. FOCUS/View enables us to clarify different levels of those mappings (the benefits (c) and (e)). We present an overview of the document search system based on them which enables users to access documents about functions which are annotated with the terms defined in either of those taxonomies. Section 6 discusses related work followed by the concluding remarks.

2. OVERVIEW OF THE FRAMEWORK

Figure 1 shows an overview of the framework proposed in this research with FB [9] as an example. This figure shows a portion of each element for simple explanation. FOCUS/View consists of two main parts: the kinds of criteria for classification (the upper left) and the values for classification (the upper right). Each of them is organized as an *is-a* hierarchy (general-specific relationship).

Generally, a level of classification in a taxonomy (or an ontology) can be explained using a pair of a classification criterion and its values. For example, 'human' class can be classified into 'man' and 'woman' sub-classes based on the classification criterion 'sex' with its values 'male' and 'female', respectively. Such a criterion of classification represents a viewpoint or a principle for that classification. The classification values for the sibling sub-classes explain the differentia among them.

Using this FOCUS/View, we can explicate classification criteria of a functional taxonomy. In Fig. 1, the lower left shows a portion of the original classification of FB in the table form [9]. The lower right part shows a result of applying FOCUS/View, that is, the FB with explicit classification criteria. A blue circle node shows a functional term. A red rectangle shows a criterion for each classification. A yellow rectangle shows a value for each term. For example, the 'branch' is classified into 'separate' and 'distribute' according to the classification criterion of "distinguishability of operands" with its values: "possible" and "impossible", respectively. These classification criteria and their values are defined in FOCUS/View. The 'separate' is further classified into three sub-terms based on two criteria "pattern of focus on operands" and "the sameness of kinds of operands". We discuss the detail of such classification

[1] This is an abbreviation of "a Functional Ontology for Categorization, Utilization and Systematization" of functional knowledge. For an overview of this project, please refer to http://www.ei.sanken.osaka-u.ac.jp/topics/Focus.

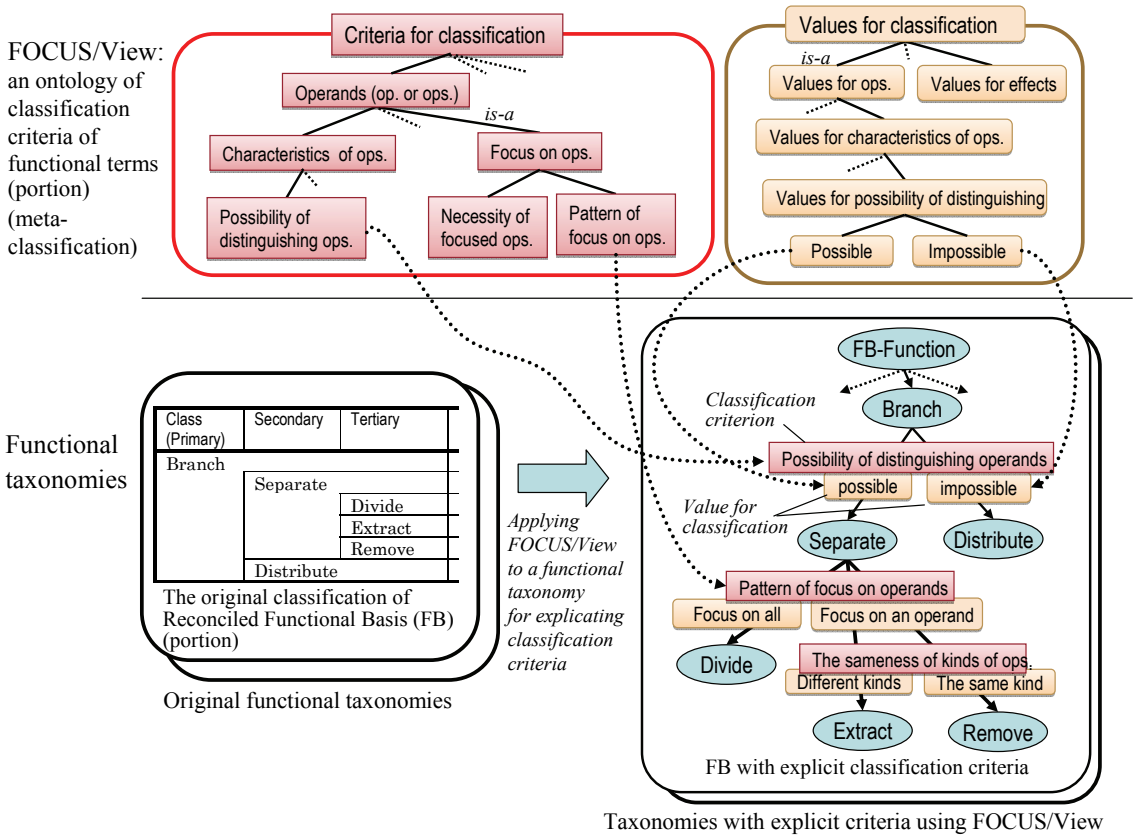

Figure 1. An overview of FOCUS/View with Reconciled Functional Basis (FB) as an example of a target taxonomy.

criteria in FB in Section 4.1.

In this manner, FOCUS/View enables us to make criteria for classification clearer. Each taxonomy uses specific criteria in a specific order in its hierarchy. FOCUS/View is a classification (hierarchy) of elements for classification of functional terms. In this sense, we can call this 'meta-classification'.

3. FOCUS/VIEW

This section presents the detail of the FOCUS/View ontology. We have established this ontology by analyzing FOCUS/Tx and FB mainly. Firstly, we built a base-model for behavior and function, which is a basis for identifying the criteria. This base-model is a generalized model which covers FOCUS/Tx, FB and other device-oriented functional modeling. Secondly, we retrieved actual criteria used in FB or FOCUS/Tx. Lastly, we organized them into a hierarchy.

3.1. Base-model

Figure 2 shows a base-model assumed for FOCUS/View. This is based on a device-oriented viewpoint, which is commonly adopted in many functional taxonomies. The behavior (or *effect (E)*) of a device is defined as the objective (without designer's intention) interpretation of its input-output relation as a black box. A device is connected to another device through its input or output ports. A device as an *agent (A)* changes states of things input (called *operands (O)*) such as substance like fluid, energy, motion, force and information (In FB, they are called *flows*). The input-output relation of the behavior is, to be exact, the difference between the states of the operands at the input port (*location, L*) and time (*time point, T*) and those at the output port and time. A device can consist of sub-devices which are connected through their ports. So, a device can be a component, an assembly, a sub-system and a system as a whole.

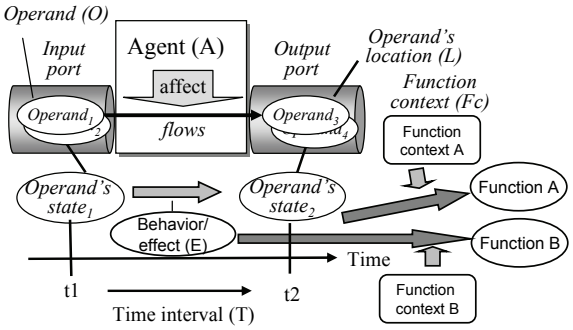

Figure 2. The base-model of function for FOCUS/View

In the FOCUS framework, the notion of "function" is defined as a role played by the behavior under a teleological context (called *function context (Fc)*) [20][2]. A function context depends on either an intention of users (or designers) or the overall function of the whole system. A function of the whole system is dependent on a user's (or designer's) intention, while a function of a component in a system is dependent on the system's function.

Using this base-model, we do not intend to enforce this definition of function to other taxonomies. The base-model just

[2] This definition is a precise version of our previous definition "a function is a result of teleological interpretation under a goal" [18]. This definition is of the base-function for an operand. We define meta-functions for other function [19] as well. In this paper, we concentrate on the base-function.

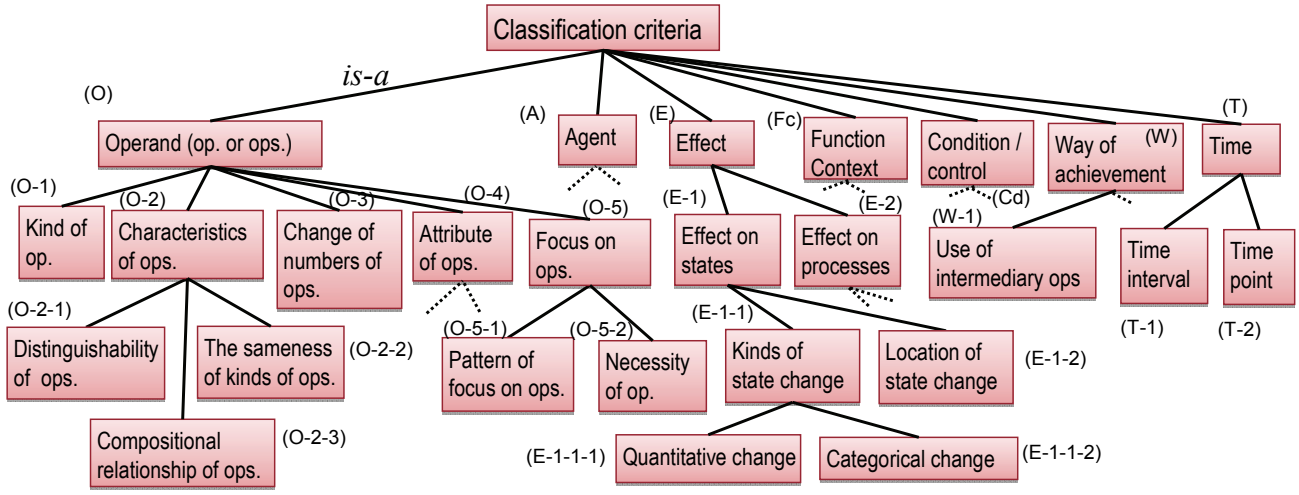

Figure 3. Classification criteria defined in FOCUS/View (portion).

represents an assumption that a function is dependent on a purpose, i.e., either the user's intention or the system's function, which is represented as a *function context.* Such intention-relatedness of function is captured in the literature as "aims-means" [2] "means and ends" [4], F-B relationship [6] and in value engineering [1]. We have investigated other definitions of function and clarified the relationship among them in [22][25].

3.2. Elements of FOCUS/View

Based on the base-model, we have investigated definitions of FB and FOCUS/Tx and then have conceptualized their classification criteria. Figure 3 shows a portion of FOCUS/View. Almost all of the top-level elements (classification criteria) correspond to the basic elements in the base-model discussed above: agent (A), operand (O), effect (E), function context (Fc) and time (T).

For example, the node (O) represents a super-class of the criteria concerning the *operand*(s) (In the figures, it is abbreviated to 'op' or 'ops'). Its sub-node (O-1) represents a criterion related with the kinds of the operand(s). For instance, 'transfer' in FB is classified into 'transport' and 'transmit' based on this criteria according to the values 'material' and 'energy', respectively. The node (O-5) represents the criteria concerning "focus on operands". When we capture a function of a device, we sometimes focus on specific operand(s) among the operands of the device. Depending on its pattern (the criterion O-5-1), FB classifies 'separate' into 'divide', 'extract' and 'remove' as discussed in Section 4.1. FOCUS/Tx uses the same (O-5-1) criterion for classification of 'separate' into 'take-out$_2$' and 'divide' as shown in Section 4.2.

The "effect" (E) node represents a super-node of classes of the classification criteria for the effect in the base-model. It has sub-classes such as "quantitative change" (E-1-1-1) and "categorical change" (E-1-1-2) for classification based on the kinds of state-change of the operands.

The "condition/control" (Cd) criterion is concerned with the precondition of the effect and/or controlling the effects. The "way of function achievement" (W) represents the background knowledge such as physical principle in functional decomposition, in which micro-functions achieve a macro-function [20]. It represents "how to achieve a function", the authors believe, which should be distinguished from function (what to achieve). We will revisit this issue in Section 4.1.

4. APPLYING FOCUS/VIEW TO THE EXISTING TAXONOMIES

This section presents the results of applying FOCUS/View to some existing functional taxonomies.

4.1. Reconciled Functional Basis

Reconciled Functional Basis has been proposed by Hirtz et al. [9], which is a result of reconciliation of some previous taxonomies and empirical generalization based on a great number of empirical studies. The functional taxonomy of FB consists of 52 terms in three levels of classification. Each of functional terms is defined in natural language with examples and correspondents (synonyms). Table 1 shows a portion of those functional terms with their definitions [9]. As mentioned in Introduction, such a definition in natural language is sometimes ambiguous and it is difficult to distinguish similar terms. In addition, some logical issues of the classification have been found by explicating the classification criteria using FOCUS/View.

Figure 4 shows a portion of the result of applying FOCUS/View to FB, i.e., FB with explicit classification criteria defined in FOCUS/View. The authors have identified them according to the definitions shown in Table 1 and the given examples in [9] as own interpretation of them. The top-level classification of FB has no unique principle for classification. Among them, the terms 'branch' and 'connect' are distinguished according to the (O-3) criterion "change of numbers of operands". The both 'branch' and 'connect' are further classified according to the same criterion (O-2-1) "distinguishability of operands" (into 'separate'/'distribute' and 'couple'/'mix', respectively). The 'separate' is further classified into 'divide', 'extract' and 'remove'. While the definitions of 'extract' and 'remove' mention a specific operand ("to draw ... a flow" and "to take away a part of a flow ..", respectively), the definition of 'divide' does not (see Table 1). So, this classification of 'separate' seems to be based on "the patterns of focus on operands" (O-5-1). This criterion alone, however, cannot distinguish between 'extract' and 'remove'. So, this classification needs extra criterion. It seems to be 'the sameness of kinds of operands" (O-2-2) according to their definitions, examples and the informal discussion with some of the developers of FB (see the acknowledgement section). The 'remove' seems to be intended to use for the case where a flow is separated from the

Table 1. Original organization and definitions of functional terms of Reconciled Functional Basis [9] (portion)

Primary	Secondary	Tertiary	Definition (portion)
Branch			"to cause a flow to no longer be joined or mixed"
	Separate		"to isolate a flow into distinct component. The separated components are distinct from the original flow, as well as each other."
		Divide	"to split up a flow into parts or to classify distinct arts of a flow."
		Extract	"to draw, or forcibly pull out, a flow."
		Remove	"to take away a part of a flow from its prefix place."
	Distribute		"to cause a flow to break up. The individual bits are similar to each other...."
Connect			"to bring two or more flows ... together."
	Couple		"to join or bring together flows such that the members are still distinguishable from each other"
		Join	"To couple flows together in a predetermined manner."
		Link	"To couple flows together by means of an intermediary flow"
	Mix		"To combine two flows into a single, uniform homogeneous mass."
Change			"to adjust the flow in a predetermined and fixed manner"
	Increment		"to enlarge a flow"
	Decrement		"to reduce a flow"
	Shape		"to mold or form a flow"
	Condition		"to render a flow"

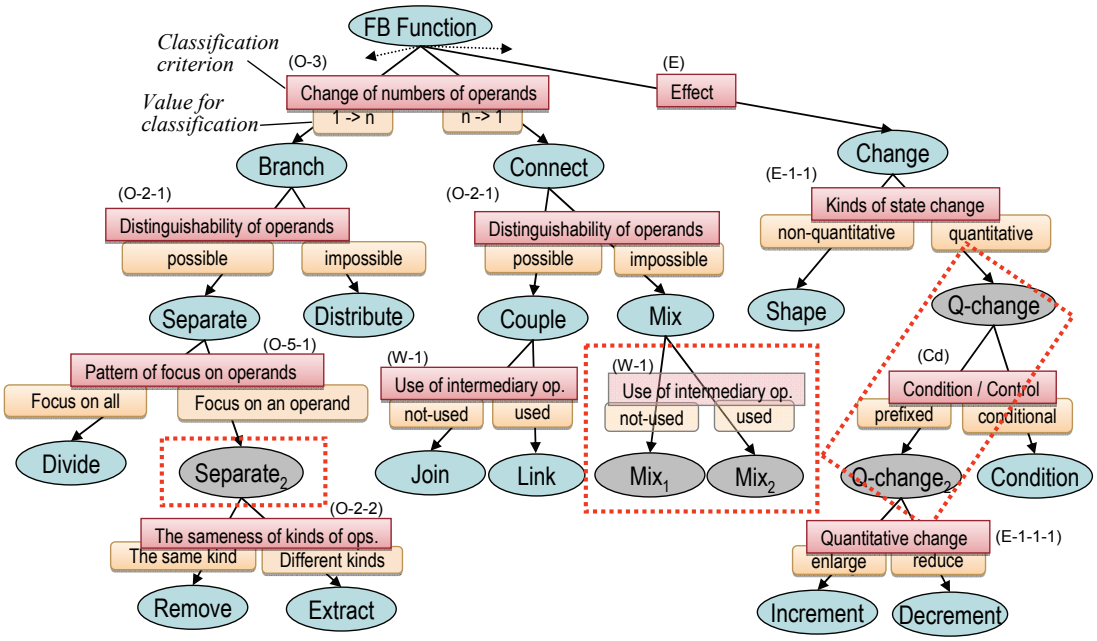

Figure 4. Reconciled Functional Basis (FB) with classification criteria defined in FOCUS/View (portion). This is logically modified according to these criteria. (the gray nodes have been inserted)

same kind of flow, while 'extract' seems to be intended to use for the case where a flow is separated from the different kind of flow(s).

This classification is problematic from the viewpoint of logic and ontological engineering. As a principle of ontological engineering, classification of a concept into its direct sub-concepts should be based on a single criterion. If we apply this principle, an intermediate term is needed to be inserted as shown as "separate$_2$" with gray in Fig. 4 (The suffix number 2 in "separate$_2$" is added for distinguishing from 'separate').

The 'couple' is classified into 'join' and 'link'. According to the definition and the example of 'link', the flows are coupled together *by means of* an intermediary operand (flow) such as a turnbuckle. So, this classification is based on "how to achieve a function". We distinguish this from function (what to achieve) and then call "the way of function achievement" as mentioned above. Thus, the criterion of this classification is "use of intermediary operand" (W-1 in Fig. 3) which is sub-class of "the way of function achievement" (W). The authors believe that these functional terms that imply ways of function achievement do not represent pure functions and thus exclude such terms from FOCUS/Tx as discussed in the next section.

In addition, if we think the logical symmetry is important, this criterion (W-1) should be applied to 'mix' and then we would have two sub-nodes ('mix$_1$' and 'mix$_2$' in Fig. 4).

In the original FB taxonomy shown Table 1, 'change' is directly classified into 'increment', 'decrement', 'shape' and 'condition'. Obviously, this classification is based on multiple criteria. The right part of Fig. 4 shows a possible logical classification, in which a level of classification is based on a single criterion and then two intermediate terms ('Q-change' and 'Q-change$_2$') have been inserted.

In this manner, FOCUS/View helps us make classification criteria clearer and suggest possible logical improvement of

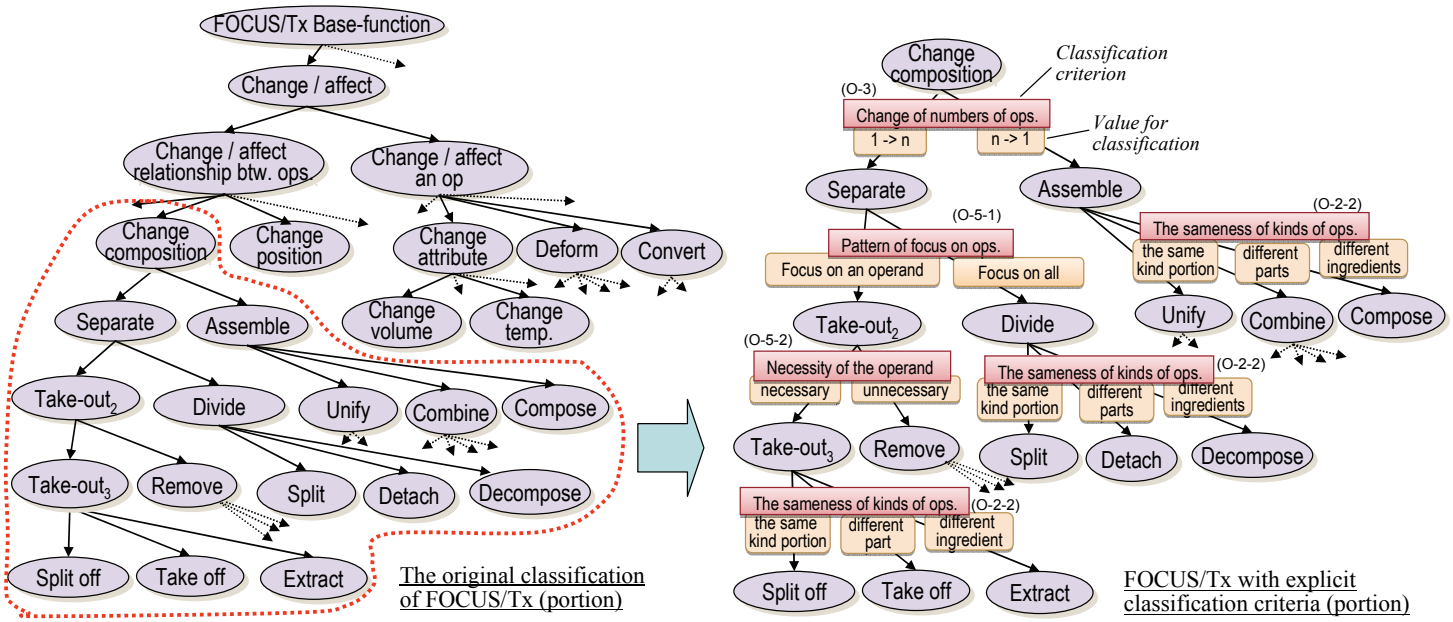

Figure 5. Classification criteria of FOCUS/Tx (Portion)

taxonomies. Note that these classification criteria are the author's interpretation of the original definitions in [9] as an example of application of FOCUS/View. Thus, the authors do not claim their correctness. In addition, the suggested modifications here are from purely logical point of view. The authors also do not claim that appropriateness of those inserted terms and their usefulness from the engineering point of view. These are different issues and should be in nature verified by empirical study and/or practice in industry as discussed in Section 6.

4.2. FOCUS/Tx

FOCUS/Tx defines generic types of the base-functions (called functional concepts in the ontology. They correspond to functional terms in this paper). The left part of Fig. 5 shows its portion. A functional concept (a class of function) is defined ontologically using constraints on the cardinality of operands, relationships among them and/or designer's intention to change (focus of intention). For example, a function "to divide an operand" is defined by the following semantic constraints: (1) the cardinality of the input focused operand must be 1, (2) the cardinality of the output focused operands must be greater than 1, (3) there must be material-product relationship between the input operand and the output operands and (4) all the output operands are equally focused. The first three are inherited from the super-concepts such as 'separate'. The fourth one enables us to distinguish the 'divide' function from the sibling function 'take-out$_2$'. This ontology has been implemented using an ontology editor Hozo[3] in its own language and in OWL and SWRL languages. In these implementations, although those definitions are clear, the classification criteria and its values are not explicitly conceptualized.

Using FOCUS/View, we can make the classification criteria clearer as shown in the right part of Fig. 5 (Only subclasses of 'change composition' are shown). Thanks to FOCUS/View, we can easily understand that the same O-2-2 criterion "the sameness of the kinds of operands" is used for the classification of three functional terms: 'assemble', 'divide' and 'take-out$_3$' in FOCUS/Tx as shown in Fig. 5. In addition, FB also uses the same criterion for the classification of 'separate' (precisely speaking, the distinction between 'extract' and 'remove') as discussed in the previous section. In this manner, FOCUS/View provides *clues* for easy understanding of a taxonomy and easy comparison among different taxonomies.

The criteria used in FOCUS/Tx cover almost all of the criteria used in FB with some exceptions. These exceptions can be explained by the fact that some criteria imply different ones and the policy that FOCUS/Tx excludes the functional terms that are classified according to one of "a way of function achievement" criteria (W criteria in Fig. 3) as discussed above. Thus, these W criteria are never used in FOCUS/Tx. From this observation, we can say that FOCUS/Tx covers FB sufficiently. This fact is very interesting, considering the following backgrounds of these taxonomies. They have been developed independently from each other using different natural languages for terms (FOCUS/Tx is designed firstly in Japanese, while FB is designed for (and defined by) English). We revisit this result with the mapping result in Section 5.1.

4.3. Krumhauer's functions and Roth's ones

The classification of the Krumhauer's generally valid functions is explained in the book [5] that it is based on differences between input and output of (1) type, (2) magnitude, (3) number, (4) location and (5) time as shown in the left part of Fig. 6. Their classification criteria can be represented using FOCUS/View as shown in the right part of Fig. 6 with intermediate nodes (depicted with gray) for logical clearness. As you can see, the original one-level classification implies many different criteria.

The Roth's generally valid functions shown in [5] use almost the same criteria as ones used in the Krumhauer's function. The difference is that the criterion "quantitative change" is not used in the Roth's classification. So, in a manner similar to Fig. 6, we can explicate its classification criteria.

Consequently, FOCUS/View can explain these taxonomies other than FB and FOCUS/Tx which we have investigated for

[3] http://www.hozo.jp

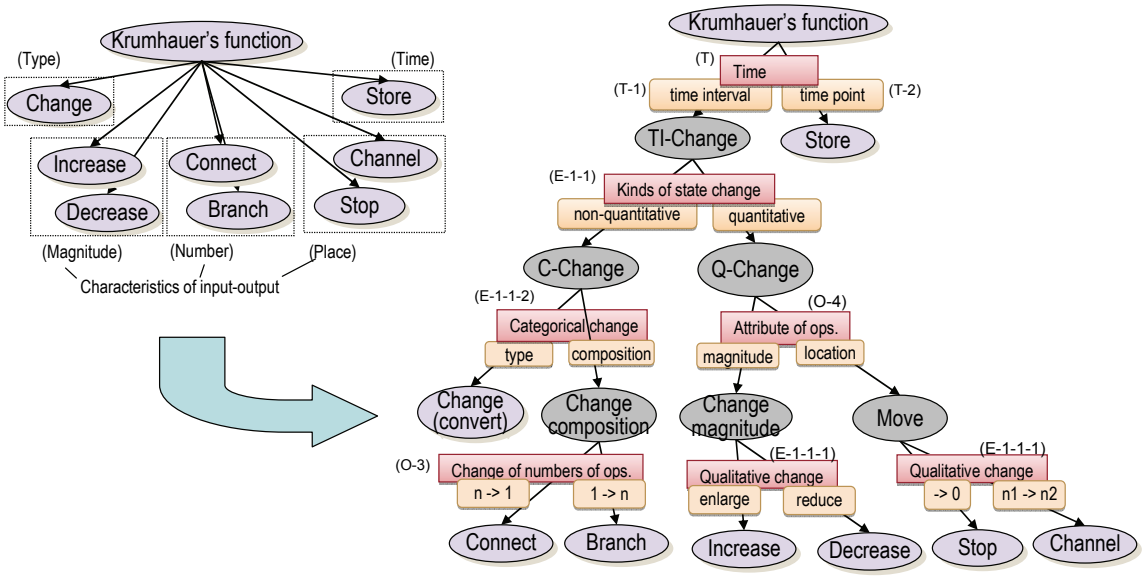

Figure 6. Classification criteria of Krumhauer's generally valid functions.
(Left) Original classification [5], (Right) Re-organization using FOCUS/View with inserted terms (the gray nodes)

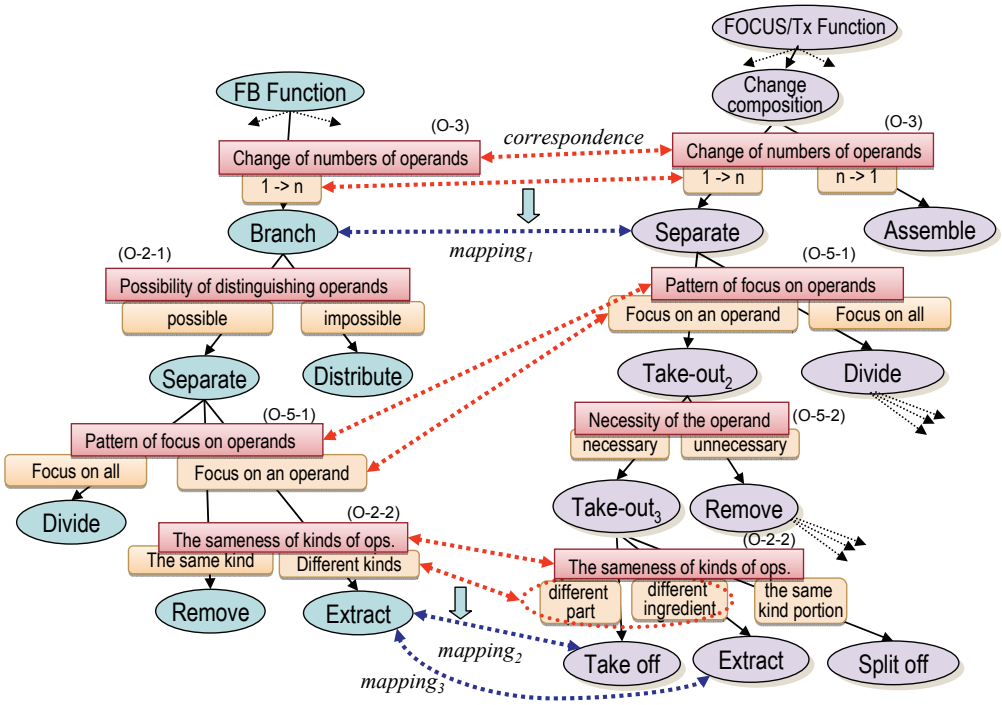

Figure 7. Mappings between Reconciled Functional Basis (FB) and FOCUS/Tx based on FOCUS/View.

the construction of FOCUS/View. This suggests a level of generality of FOCUS/View for representing classification criteria of functional terms. Of course, we do not claim its comprehensiveness for all functional taxonomies. Applying it to other existing functional taxonomies such as those in [4][12] and further investigation on its generality remain as future work.

5. USING FOCUS/VIEW FOR MAPPINGS BETWEEN TAXONOMIES

5.1. Mapping between FB and FOCUS/Tx

The explication of the classification criteria facilitates comparisons between different functional taxonomies and then establishment of mappings between functional terms of them. The mappings between functional taxonomies enable us to realize interoperability between them. In our previous papers [23][24], we presented mappings between FB and FOCUS/Tx. In this paper, we suggest FOCUS/View makes mapping easier and more accurate than previous mappings.

Figure 7 shows some examples of the mappings between FB and FOCUS/Tx terms based on FOCUS/View. We have established a set of a *correspondence mapping* between a term of FB and a term of FOCUS/Tx, which have similar meanings. Finding corresponding terms has been manually done based on the explicit classification criteria using FOCUS/View. For ex-

ample, as shown in the upper part of Fig. 7, we can establish a mapping (denoted by $mapping_1$) between 'branch' of FB and 'separate' of FOCUS/Tx, since their classification criteria and their values are the same. We can say that this type of mappings shows *exact correspondence*.

On the other hand, in the lower part of Fig. 7, both the $mapping_2$ between 'extract' of FB and 'take off' of FOCUS/Tx and the $mapping_3$ between 'extract' of FB and 'extract' of FOCUS/Tx are not *exact* one. The classification criterion for these terms is the same ("the sameness of kinds of ops." (O-2-2)). The values for the classification are, however, different. 'Extract' of FB is based on 'the different kind' as the value, while 'take off' and 'extract' of FOCUS/Tx are based on more fine-grained values: 'different part' (such as change by structural decomposition) and 'different ingredient' (such as change by a chemical reaction), respectively. So, we can say that these mappings represent *rough correspondence* between them, which are different from the *exact correspondence* such as $mapping_1$ discussed above.

In this manner, the explicit classification criteria using FOCUS/View facilitate more reliable mappings between functional taxonomies. In addition, it enables us to show the difference of the degrees of the exactness of the mappings.

As reported in [24], in the mappings from FB to FOCUS/Tx, the terms in FB cover (have mappings to) 33 terms in FOCUS/Tx out of the total of 89 (37%). Its success rate was calculated about 80% when the paper was written (please refer to the paper [24] for the criteria for calculation of this success rate). In the mappings from FOCUS/Tx to FB, the terms in FOCUS/Tx cover 43 terms in FB out of the total of 52 (83%). Its success rate was calculated about 70% excluding the terms in the different grain-sizes.

Using FOCUS/View, we can analyze more accurate success rate of mappings based on the degree of the exactness of the mappings. For example, among the successful mappings from FB to FOCUS/Tx reported above, it turned out that 7 mappings are *rough correspondences*. So, if we regard only *exact correspondences* as successful mappings, the accurate success rate would be 75%.

These success rates are still regarded as very high, considering the background of these taxonomies mentioned in Section 4.2. Consequently, both of these success rates and the high coverage ratio of the classification criteria discussed in Section 4.2 strongly suggest the validity of the content of both FOCUS/Tx and FB from their commonality. The suggested validity is supported by their applications as well. FB is widely used and has many empirical studies. FOCUS/Tx has been deployed in manufacturing companies in Japan [20].

5.2. Interoperability using mappings of taxonomies

The mappings between functional taxonomies can improve interoperability of functional knowledge. We have developed a semantic document search system (named *Funnotation Search System*) [21] which can provide engineers with interoperable access to annotated technical documents by searching for functional terms based on the mappings between FB and FOCUS/Tx [24]. On the basis of the Semantic Web technology, technical documents are annotated with metadata using functional terms defined in either FB or FOCUS/Tx. By translating the functional terms in the query and the metadata annotated with documents, the search system can access both documents that are annotated based on either FB or FOCUS/Tx. Figure 8 just shows a search result when a user gives 'split' of FOCUS/Tx as a search word. It includes not only documents annotated with 'split' of FOCUS/Tx but also those documents annotated with 'distribute' of FB which has a mapping to 'split' of FOCUS/Tx. Please refer to the papers [21][24] for the detail of the *Funnotation* framework.

Using FOCUS/View, the user can check the exactness of the mappings and select documents with the exact correspondence only according to his or hers intention.

6. DISCUSSION AND RELATED WORK

The ultimate goal of this research is to enumerate possible classification criteria of functional terms. On the other hand, Reconciled Functional Basis is a result of merging two existing taxonomies aiming at a 'standardized taxonomy' [9]. We aim at clear comparison between different taxonomies based on the

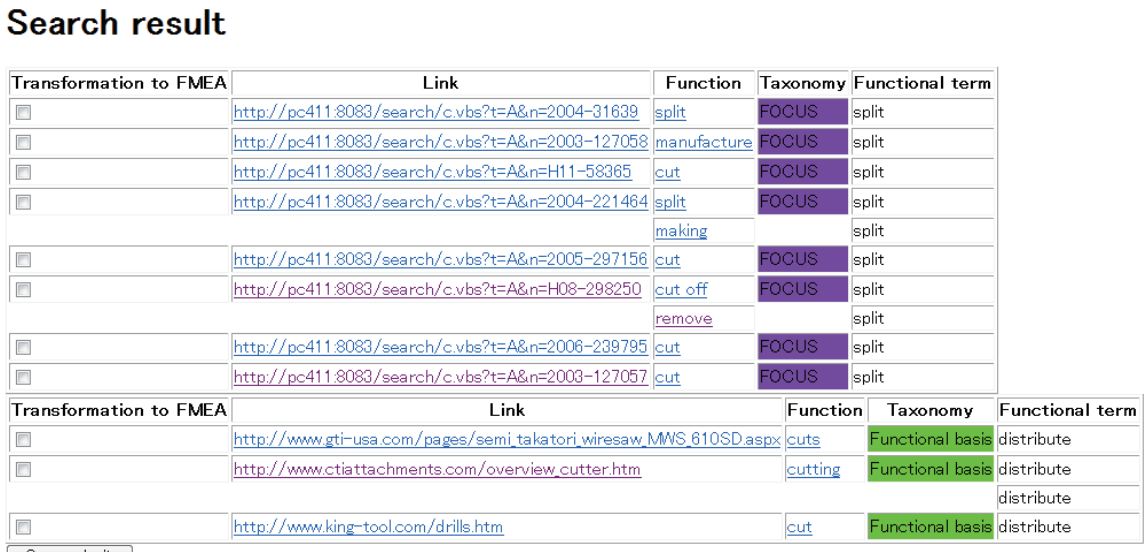

Figure 8. Interoperable search result by the *Funnotation* system based on mappings between functional taxonomies.

enumerated classification criteria and establishing mappings ('ontology matching' in the terminology of [27]) rather than merging ('ontology merging'), in order to allow the diversity of conceptualization of functions and their classification. Thus, FOCUS/View provides not a super-set (logical sum) of the existing taxonomies but generic and common classification criteria used in functional taxonomies.

As pointed out in [28], a "shared ontology" can facilitate semantic integration. The top-level generic ontologies such as DOLCE[4] and YAMATO[5] can be used as the shared ontology. Our FOCUS/View also can be regarded as a kind of such a shared ontology for matching concepts in ontologies, though a functional term of a functional taxonomy is not a subtype of a class defined in FOCUS/View but is used as criteria for classification. In this sense, the top-level ontologies are at *super-level*, while FOCUS/View is at the *meta-level*.

ONIONS methodology [29] is pioneering work to integrate terminologies based on formal and generic ontologies. It includes the "conceptual analysis" phase, in which the entities of a source terminology are represented in a formal way. Although our approach is not based on formal and generic (top-level) ontologies for integration, the explication of classification criteria using FOCUS/View corresponds to a kind of the conceptual analysis.

Some logical, semantic, formal, or mathematical definitions of functional taxonomies have been proposed in the literature (e.g., [30][31]). In [30], the FB terms are semantically defined using the Semantic Web technologies such as OWL and SWRL. In [31], some of FB terms are defined in a set-theoretic notation. Both research efforts aim at automatic reasoning such as consistency checking. FOCUS/Tx also has ontological definitions of its functional terms. The main aim of FOCUS/View is to uncover classification criteria of taxonomies which have been left implicit rather than to define each functional term for such automatic reasoning. In addition, the definitions in [30][31] capture only differences between input-flows and output-flows (the operands in our terminology). FOCUS/View includes rich concepts organized in an *is-a* hierarchy as categorization criteria from other aspects for capturing functions and thus enables us to clarify deep conceptual criteria for categorization more richly.

Garbacz proposes an ontologically-refined FB based on some ontological upper-level distinctions defined in DOLCE [26]. The proposed taxonomy has clear ontological classification criteria at the upper-level. FOCUS/View aims at more concrete-level classification for engineering practice.

Ideally (please refer to the following paragraph for a limitation), any functional taxonomies can be built by selecting a classification criterion and their value sets from those defined in FOCUS/View for each level of classification and by determining a specific order of applying these classification criteria for organizing a hierarchy.

Of course, the authors have no intention to claim that the comprehensiveness and/or completeness of the classification criteria defined in FOCUS/View. Firstly, the comprehensiveness of such an ontology can be evaluated in nature not by a theoretical way but by an empirical way. Secondly, as a limitation of FOCUS/View, its elements shown in Section 3.2 are mainly for a device-oriented modeling of function, which is discussed as the base-model in Section 3.1. In fact, the base-model of FOCUS/View is a simplified version of more generic model discussed in [22]. In that paper, we have discussed different conceptualizations (definitions) of the notion of function (such as environment function [7]) other than device-oriented one. Then, we have proposed an ontology of definitions of function in a hierarchical manner, which is called a reference ontology of function (FOCUS/Ref) [22]. Other function representation frameworks such as [6][8][11] would be explained not at the level of FOCUS/View but at the level of FOCUS/Ref. The top-level of FOCUS/View can be used for explanation of the classification of FOCUS/Ref as well. The integration of FOCUS/View and FOCUS/Ref remains as future work.

In this paper, a functional taxonomy is analyzed from a logical point of view, though as we noted in Introduction neither evaluation of the existing taxonomies nor criticism on them is our aim. Generally, a functional taxonomy can be evaluated by empirical way or by industry practice. The examples of such evaluation can be found in [32][33].

7. CONCLUDING REMARKS

In this paper, we proposed an ontology of classification criteria of functional terms in functional taxonomies based on investigation on two existing taxonomies (i.e., FB and FOCUS/Tx). We applied the ontology to other existing taxonomies as well as those taxonomies. As shown in Section 4, the ontology's application to those taxonomies clarifies the classification criteria implicit in their original classification. In addition, based on the analysis, some intermediate terms have been inserted, which contribute to logical clarity of each taxonomy.

From the viewpoint of design knowledge management, the ontological clarification of the classification criteria of functional taxonomies contributes to interoperability between them by establishing more reliable mappings between terms defined in them. We presented the interoperable document search system based on such mappings.

The complete demonstration of the benefits of this kind of the ontology is in nature difficult. Among the possible benefits of the ontology listed in Introduction, the forth one ((d) checking the logical structure and its improvement) was demonstrated in the application to FB and Krumhauer's functions. The fifth and sixth ones ((e) mapping and (f) interoperability) were demonstrated using the mappings between FB and FOCUS/Tx and the implemented document search system. The first one ((a) scientific contribution to understanding of function) is in nature difficult to be proved. The proposed ontology, however, explicates (at least) some criteria, which have been implicit in the some existing taxonomies. This ontology is the first and important step towards comprehensive understanding of classification of functional terms.

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[4] http://www.loa-cnr.it/DOLCE.html

[5] http://www.ei.sanken.osaka-u.ac.jp/hozo/onto_library/upperOnto.htm

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