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SUPPORTING FUNCTIONAL KNOWLEDGE EXCHANGE BETWEEN FUNCTIONAL TAXONOMIES BY ESTABLISHING FUNCTION-BEHAVIOUR LINKS

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ABSTRACT

This paper reviews a methodology developed by Kitamura, Mizoguchi and co-workers for the conversion of functional models between functional taxonomies. They apply their methodology to the conversion of functional models described in terms of the Functional Basis taxonomy into functional models described in terms of the Functional Concept Ontology taxonomy. It is argued in this paper that these conversions lead to information loss. Specifically, some features of Functional Basis models are incompatible with Functional Concept Ontology models, and their removal is the only option available in these conversions for resolving incompatibilities. An alternative strategy is presented that solves this information loss. Model conversions are carried out under the assumption that the meaning of the concept of function in the Functional Basis and the Functional Concept Ontology is the same. This paper argues instead that it differs in meaning and explains the incompatibilities in terms of this difference. Specifically, Functional Basis-functions correspond to desired physical behaviours whereas Functional Concept Ontology-functions correspond to roles of behaviours. Based on this distinction, a two-step strategy is presented that retains Functional Basis-information. Firstly, Functional Basis-functional models are converted into behavioural models. Secondly, behavioural role models are abstracted from converted behavioural models.

KEYWORDS

Functional modelling, knowledge exchange, function-behaviour link, behavioural model-conversion, functional model-abstraction

1. INTRODUCTION

As can be seen in a current review by Erden et al. [1] engineering design research has produced an impressive wealth of functional modelling approaches. In these approaches also a variety of definitions of functions, representations for functions and strategies for decomposing functions into sub functions are proposed. For instance, Chakrabarti [2] and Deng [3] distinguish functions corresponding to intended behaviours from functions corresponding to purposes. With regard to the representation of functions, Chakrabarti and Blessing [4] identify three frameworks that are in use in engineering: verb-noun representations, input-output flow transformations, and input-output state transformations. Exponents of these representational frameworks are, for instance, the function-behaviour-state approach of Umeda et al. [5] in which verb-noun representations are used, the systematic approach of Pahl and Beitz [6] in which input-output flow transformations are employed and the adaptive design approach of Goel and Stroelia [7] in which functions are represented by input-output state transformations. More recently, Deng et al. [8, 9] and Deng [3] have added to this representational diversity by proposing the concepts of action and input-output flow of action transformation to represent functions. Concerning the decomposition of functions into sub functions, Van Eck et al. [10] distinguish strategies in which functional decompositions are developed in a solution-neutral fashion from strategies in which known technical solutions for sub functions are incorporated from the outset.

A current research theme within functional modelling research concerns the development of methods that support the exchange and sharing of functional knowledge, both between engineering design teams and between members of design teams. The emerging field of engineering function ontology aims to facilitate knowledge exchange by developing function ontologies, in which specific concepts of technical function are formalized [11,12,13,14]. Function ontologies prove useful in the storage, retrieval and communication of functional information between engineers and engineering teams using the same ontology [13]. With regard to this exchange and sharing of functional knowledge one can identify a challenge in the engineering literature though. These function ontologies are framed *within* the confines of a specific functional modelling approach or taxonomy, each with their own definition of function and schemes for representing functions. It is however commonplace that different meanings are attached to the concept of function in the engineering domain [1,15,16,17], and acknowledged that this diversity poses challenges to the establishment of knowledge exchange *between* different functional frameworks [3,18].

A methodology, developed by Kitamura et al. [19,20] and Ookubo et al. [21] is specifically aimed at establishing functional knowledge exchange across different functional frameworks by bridging such different conceptions of technical function *between* different functional taxonomies. Their *conversion methodology* does so by converting functional models between functional taxonomies. Ookubo et al. [21] and Kitamura et al. [19,20] apply their methodology to a conversion of functional models described in terms of the Functional Basis (FB) taxonomy of Stone and Wood [22] into functional models described in terms of the Functional Concept Ontology (FCO) taxonomy of Kitamura et al. [13]. In this paper I review these FB-FCO model conversions and argue that they harbour a problem: they lead to information loss. Specifically, it will be shown that some features of FB models are incompatible with FCO models, and that removal of these model features is the only option available within the structure of the conversion methodology to resolve them. Removal of these model features leads to information loss. In effect, FB-FCO model conversions only partially establish their purpose of exchanging functional information between the FB taxonomy and the FCO taxonomy. This paper presents an alternative strategy for solving this information loss. Model conversions are carried out under the assumption that the meaning of the concept of function in the FB and the FCO is the same [19,21]. This paper argues instead that it differs in meaning and explains the incompatibilities in terms of this difference. Specifically, FB-functions correspond to desired physical behaviours whereas FCO-functions correspond to roles of behaviours. Based on this distinction, a two-step strategy is presented that retains FB-information. In the first step, FB-functional models are converted into behavioural models. In the second step, behavioural role models are abstracted from converted behavioural models. It is argued that this strategy establishes knowledge exchange between the FB and FCO taxonomies *without information loss*.

The main research problem tackled in this paper is the establishing of knowledge exchange across functional frameworks in a way that minimizes information loss. The research method adopted in this paper to his end is conceptual and example-based. The conceptual structure of the conversion methodology and the FB and FCO taxonomies is analysed. This analysis is then used to compare conceptual differences between the FB and FCO taxonomies. And to present an alternative conceptual strategy for knowledge exchange across functional frameworks. The benefits of this alternative proposal are then assessed in terms of a comparison of examples of stapler models as discussed in the conversion methodology and as developed in my proposal. Like my research method, this assessment is of a conceptual nature. Further empirical validation is left with the relevant experts.

The paper is organized as follows. A brief survey of the literature on function-behaviour abstractions is given in section two. The FB approach and the FCO approach are presented in section three. The conversion methodology and model conversions between the FB and FCO taxonomies are discussed in the fourth section, and illustrated by a conversion of a stapler model. The problem of information loss is specified in section five. The solution to this problem is given in the sixth section. The paper ends with conclusions in section seven.

2. SURVEY

A substantial amount of research has been carried out on the relation between function and behaviour and the abstracting of function from behaviour [see e.g. 5,16,23,24,25,26]. In this research, a key factor in understanding this relation and in abstracting function from behaviour is the notion of design intent [24]. Functions pick out those behaviours or features of behaviours that are intended by a designer. In the literature it is however acknowledged that capturing the relation between function and behaviour and abstracting the former from the latter in terms of the notion of design intent lacks rigour. Kitamura et al. [26], for instance, argue that in most proposals abstracting function from behaviour is done in an ad–hoc fashion and lacks systematic guidelines. Indeed, such abstractions are often carried out by employing archived function and behaviour-knowledge on existing designs, instead of by using explicit guidelines [10]. The work of Sasajima et al [25] and Kitamura et al. [26] is aimed to specify such guidelines, thus adding rigour to these abstractions. However, although very valuable, one can identify a similar reservation for this research as was done for engineering function ontology research in the Introduction section. These guidelines for abstracting functions from behaviours are developed *within* the context of a specific functional modelling approach. Yet – in line with the different meanings attached to the concept of function in the engineering domain – viewpoints on the relation between function and behaviour differ across approaches [27]. Given my analysis that FB-functions correspond to desired physical behaviours and FCO-functions to roles of behaviours, this sets a challenge to abstracting function from behaviour *between* different approaches. This paper takes up this challenge.

3. FUNCTIONAL MODELLING TAXONOMIES

3.1. Functional Basis taxonomy

The Functional Basis (FB) approach, formulated by Stone and Wood [22] is an approach to functional modelling that is aimed at creating a common and consistent functional design language, dubbed a functional basis. This language allows designers to model overall product functions as sets of interconnected sub functions. The FB approach is focused on especially the electromechanical and mechanical domains. The approach is presented as supporting the archiving, comparison, and communication of functional descriptions of existing products, as well as the engineering designing of new products. Since the approach was proposed it has been developed further. It is for instance used to build a web-based repository in which functional decompositions of existing products are archived, as well as components counting as design solutions for the sub functions that are part of these decompositions. The function and flow information of components archived in this repository has recently been employed by Bryant et al. [28] in building a function-based component ontology. In this ontology product components are classified based on their most commonly ascribed sub functions as archived in the repository.

In the FB approach, an overall product function refers to a general input/output relationship defined by the overall task of the product. This overall product function is described in a verb-object form and represented by a black-boxed operation on flows of materials, energies and signals. A sub function, describing a part of the product's overall task, is also described in a verb-object form but represented by a well-defined basic operation on a well-defined basic flow of materials, energies or signals. The black-boxed operations on general flows representing product functions are derived from customer needs, and the basic operations and basic flows representing sub functions are laid down in common and limited libraries that span the functional design space. These libraries are called a *functional basis*, making up the FB functional taxonomy. In 2002, the FB approach was reconciled with an approach developed by Szykman et al. [29] in collaboration with Julie Hirtz, Daniel McAdams, and Simon Szykman [30], and coined Reconciled Functional Basis.

Stone and Wood [22] present a three-step methodology to develop functional models or functional decompositions of products. The methodology starts with describing a product function in a verb-object form, represented by a black-boxed operation on flows of materials, energies, and signals. A chain of operations-on-flows is then specified, called a function chain, for each black box input flow, which transform that flow step-by-step into an output flow. These operations-on-flows are to be selected from the FB libraries. Finally, these temporally ordered function chains are aggregated into a single functional model of a product.

A FB model of a hand-held stapler is shown in Figure 1, adapted from Stone et al. [31]. This model consists of temporally ordered chains of sub functions that transform the material input flows of "hand", "staples" and "sheet", and the energy input flow of "human force", step by step into output flows.

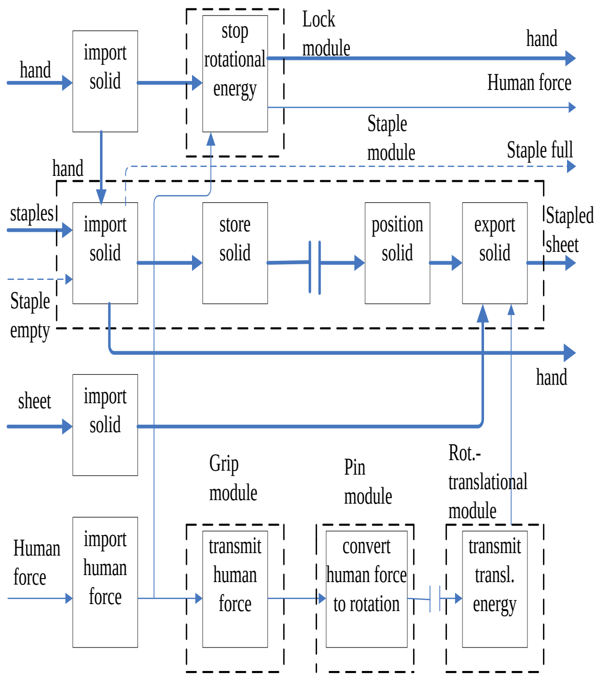

Figure 1 FB model of a stapler

3.2. Functional Concept Ontology taxonomy

The Functional Concept Ontology (FCO) approach, developed by Kitamura and Mizoguchi [32,33] and Kitamura et al. [13] is an approach to functional modelling that is aimed at facilitating the sharing of engineering functional knowledge. In this approach, in order to facilitate knowledge exchange, a set of modelling guidelines and a functional modelling language are developed to assist the systematic and reusable description of functional models of devices. These guidelines and language make up the FCO functional taxonomy. The approach supports various tasks. It is for instance employed in building an ontology for functions and in developing an automated design support system [32]. The approach is currently deployed in an engineering division of a Japanese industrial firm for sharing functional device knowledge amongst its team members [13].

In the FCO approach, both behavioural models and functional models of devices are developed concurrently. Behaviours of devices and their components are defined as input-output relations between operand states. Operands refer to energy, fluid, material, motion, force, or information. Behaviours are represented as input-output state changes of properties of operands. Both overall functions and sub functions of devices are defined as roles played by behaviours, intended by designers or by users. Functions and sub functions are represented in terms of verb-operand pairs. The functional modelling language used in this approach consists of a generic set of verbs. These verbs are called *functional concepts* [13,32].

In a functional model or functional decomposition a set of sub functions is specified that realize the overall function. In a functional decomposition it is furthermore specified by means of which technical principles, referring to knowledge on structures and the behaviours they exercise, the sub functions achieve the overall function. These specifications are referred to as “way of achievement” [13].

A FCO model of a stapler is shown in Figure 2, adopted from Ookubo et al. [21]. This model consists of the overall function of the stapler, and sub functions of the modules and components of the stapler. Ways of achievement are shown in the model, specifying how the component functions realize the module functions, and how the module functions realize the overall function. The module function “combine sheets and staples”, for instance, contributes to the realization of the overall function “combine sheets” by an “intermediate way” that represents the combining of paper sheets via staples acting as intermediates between the sheets.

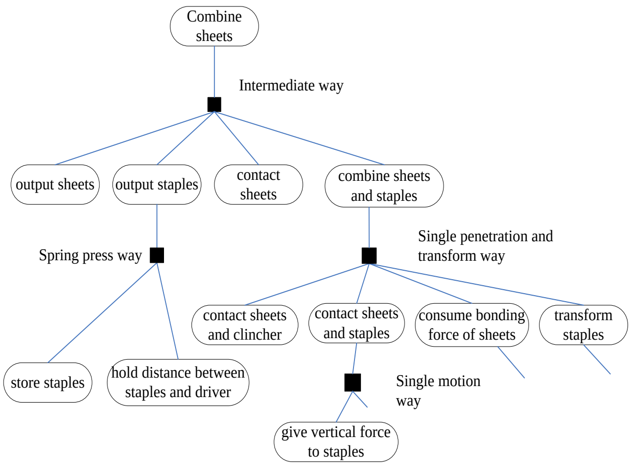

Figure 2 FCO model of a stapler

As can be seen by comparing Figure 1 and Figure 2, FB functional models differ from FCO functional models. For instance, functions in FB models are connected by the flows they take as input and output, whereas functions in FCO models are not connected by operands. The other way round, ways of achievement are described in FCO models but not in FB models. The conversion methodology is aimed to bridge these differences by converting FB models into models described in terms of the FCO taxonomy.

4. FUNCTIONAL MODEL CONVERSIONS

4.1. The conversion methodology

Kitamura et al. [19] and Ookubo et al. [21] aim with their methodology to support the conversion of a functional model *fm1*, which is based on one functional taxonomy *fx1*, into a (converted) functional model *Cfm1*, which is based on another functional taxonomy *fx2*. Functional models are converted by carrying out two steps. In the first step, the function terms of *fx1* are translated into function terms of the other taxonomy *fx2*. By this *fx1*-to-*fx2* function term translation, function terms in *fm1* are translated into function terms that will be included in *Cfm1*. In the second step, conceptual differences between models based on *fx1* and models based on *fx2* are explicated, and measures are developed and carried out to minimize these in the model conversion. By minimizing these differences Ookubo et al. [19] and Kitamura et al. [21] aim to improve knowledge exchange between *fx1* and *fx2*. After these steps a functional model *fm1* based on *fx1* is converted into a functional model *Cfm1* based on *fx2*.

In the first step, function terms are translated by using a "reference ontology" for functions [19,21]. This reference ontology is used to identify the meaning of functions that are part of functional taxonomies and, based on this identification, to translate functions between taxonomies. In this reference ontology, function categories are defined which are stated to correspond to existing engineering meanings of the concept of function. Definitions of these function categories are based upon the conceptual structure of the FCO approach [19,21]. The FCO concepts of device, behaviour, function and operand are further specified into subtypes called "descriptors of functions" [19]. With these descriptors of functions, different function categories are defined in the reference ontology. With these function categories they aim to identify different meanings of the concept of function in the engineering domain. According to Kitamura et al. [19] and Ookubo et al. [21], by first classifying the function terms from *fx1* and *fx2* into function categories their meaning can be established. This classification is done by matching the definitions of function terms of *fx1* and *fx2*, as laid down in *fx1* and *fx2*, with the function categories in the reference ontology. The function terms in *fm1* are then translated into function terms that will be part of *Cfm1*. Depending on how these function terms are classified, different sorts of translations are carried out. Translations between function terms that are classified in the same function category are presented as straightforward, since the same meaning is attached to these function terms. These translations are called "within category" mappings. When *fx1* includes function terms that are classified in a certain function category and *fx2* lacks function terms that can be classified in that same function category, translating these function terms from *fx1* to *fx2* involves more complex procedures. Such function terms (and their meaning) are namely part of one taxonomy, but not part of the other taxonomy [19,21]. These more complex translations are called "between category" mappings.

After this first translation step an interim functional model *fm** results consisting of translated function terms that are represented in terms of *fx2*. In this phase, *fm** still has the same model structure as *fm1*, i.e., all the model features of *fm1* are also represented in *fm**. In the second step, conceptual differences between models based on *fx1* and models based on *fx2* are further explicated. This is done by comparing *fm1* with a functional model of the same device that is described in terms of *fx2* functions and according to *fx2* modelling criteria. Let us abbreviate this comparison model as *fm2*. The conceptual differences identified between *fm1* and *fm2* are then used to modify *fm**, resulting in *Cfm1*.

After these translation and modification steps, a functional model *fm1* based on *fx1* is converted into a functional model *Cfm1* based on *fx2*. This conversion strategy is illustrated schematically in Figure 3.

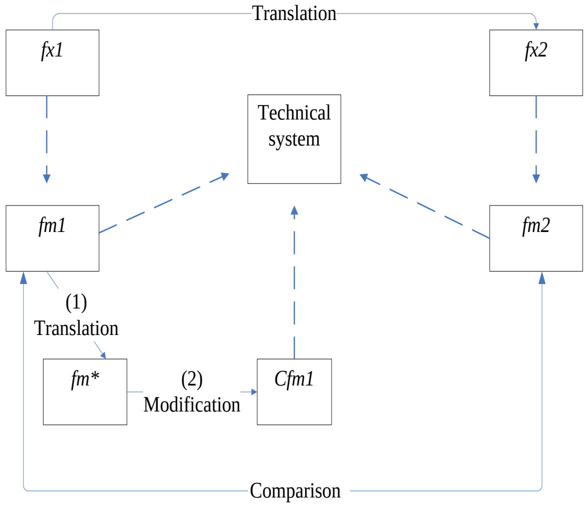

Figure 3 The conversion method

(Ookubo et al. [21] use the concept of an "interim functional model" at a conceptual level, and they do not give an example of such a model. I follow their usage of this concept here). The conversion methodology can be applied two-ways: either taxonomy may provide a functional model *fm1* that is converted by applying the method. The demonstration of the method given by Ookubo et al. [19] goes one way.

4.2. Functional Basis-to-Functional Concept Ontology model conversions

Ookubo et al. [21] demonstrate their method by a conversion of an FB model (*fm1*) of a stapler represented in terms of the FB taxonomy (*fx1*) into a (converted) model (*Cfm1*) represented in terms of the FCO taxonomy (*fx2*). They also use a comparison FCO model of a stapler (*fm2*) in this conversion. This comparison FCO model (*fm2*) is used to identify conceptual differences between models based on the FB taxonomy and models based on the FCO taxonomy.

The FB model (*fm1*), which Ookubo et al. [21] adapt from Stone et al. [31], is shown in Figure 1. The comparison FCO model (*fm2*) is shown in Figure 2 and the converted FB model (*Cfm1*) is shown in Figure 4. (I present the same adaptation of the FB model as Ookubo et al. [21] give. This adaptation consists in excluding several operations-on flows-which are described in the original FB model. The vertical lines intersecting the "human force" flow and the "staples" flow represent this exclusion).

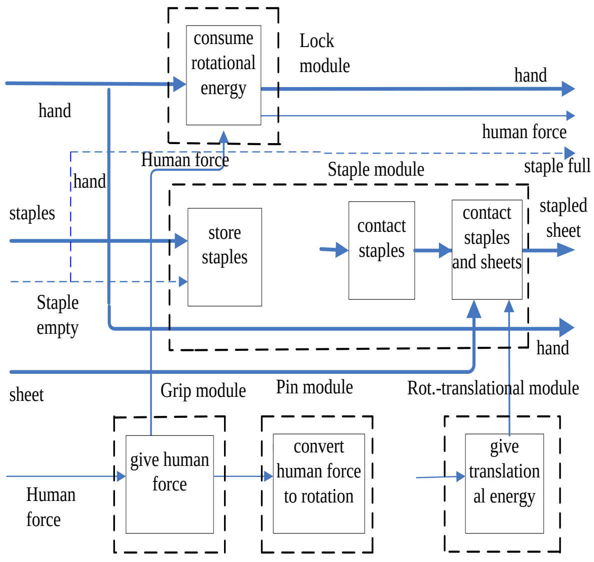

Figure 4 Converted FB model of a stapler (*Cfm1*)

In the first step of the model conversion, Ookubo et al. [21] translate functions both by "within category" mappings and by "between category" mappings. Most FB function terms and all FCO function terms are classified in the "flowing object" function category [19]. Flowing object functions correspond to a specific type of behaviour, to wit: temporal changes in attributes of a physical entity, such as matter and energy flows or operands, within a device's system boundary. A role is attached to these behaviours in a teleological context [19,21]. Since most function terms in the FB and FCO taxonomies are classified as flowing object functions, the same meaning is attached to them. These function terms are translated by "within category" mappings. An example of a within category mapping of flowing object functions in the model conversion is the FB function "transmit human force" (Figure 1) that is translated into the FCO function "give human force" (Figure 4). Some of the FB function terms in the FB stapler model are classified in the reference ontology as "system interface functions". System interface functions represent temporal changes in attributes of a physical entity on a system boundary. The FB "import" and "export" function terms are classified as system-interface functions. Since the FCO solely consists of "flowing object functions" [21], these FB function terms are translated by a between category mapping: the FB "import" and "export" operations-on-flows are translated in the model conversion into FCO input and output operands. Examples of between category translations are the "import solid (sheet)" and "export solid (stapled sheet)" functions of the FB model (Figure 1) that Ookubo et al. [21] represent in the converted FB model (*Cfm1*) as input and output operands of "sheet" and "stapled sheet" (see Figure 4). This first translation step establishes an interim model (*fm**) in which translated functions are described in terms of the FCO taxonomy, but the model still has the structure of the FB model.

Other function categories into which FB function terms are classified are the "function with way of achievement" function category and the "composite device" function category. Function terms of the FB model of the stapler are not classified in these categories. I give them here for sake of completeness. FB function terms classified as functions "with way of achievement" correspond to a flowing object function but in addition also refer to a way of achievement. An example given by Ookubo et al. [21] is the FB term "link", which has both the (flowing object function) meaning of "coupling flows together" and also refers to how this coupling is achieved, namely by an "intermediary flow". FB function terms classified as "composite device" functions correspond to a flowing object function and the meaning of the term, as defined in the FB taxonomy, can be interpreted in two different ways viewed from the FCO taxonomy. An example given by Ookubo et al. [21] is the FB term "guide" which they interpret as either referring to "supply motion" or to "change direction of motion".

After these translations, the FB model (*fm1*, Figure 1) and the comparison FCO model (*fm2*, Figure 2) are compared in the second step to identify conceptual differences between these models. Based on these differences, procedures are then developed to modify the interim model (*fm**). Six conceptual differences are identified between the FB model and the comparison FCO model [21]:

- (1) In FCO models, overall functions are related to sub functions of modules, which are related to sub functions of components. FB models do not represent relationships between sub functions of modules and components.
- (2) In FCO models, functions are not connected by operands, whereas functions are connected by flows they have as input or output in FB models.
- (3) In FCO models, ways of achievements are described, whereas these are not described in FB models.
- (4) In FCO models, changes in distance between physical objects – matter and energy flows/operands – are described, whereas these are not described in FB models.
- (5) In FCO models, features of users are not described, whereas features of users are described by human material flows in FB models.
- (6) In FCO models, material and energy operands may be grouped together in descriptions of functions, whereas material and energy flows are separated in FB models.

In the conversion of the FB stapler model, Ookubo et al. [21] develop and carry out modifications to handle the difference in distance changes between physical objects (4) and to handle the difference in user features (5). They are currently investigating modifications to handle the difference in connections between functions (2) and to handle the difference in separating vs. grouping material and energy (6). The converted FB model in Figure 4 thus is the result from the translation of functions in the first step, and from the modifications in the second step that address differences in representing distance changes between flows/operands, and differences in representing (parts of) users of devices. This model is currently the endpoint of the conversion process [21].

The difference between the FB model (*fm1*, Figure 1) and the comparison FCO model (*fm2*, Figure 2) concerning distance changes between flows/operands is handled by *adding* an FCO function from the comparison model to the interim model (*fm**). In the FB model, the "staple" and "sheet" flows enter the stapler as separate flows and exit as the combined flow "stapled sheet". The combining of these flows, referring to a change in distance between flows, is not represented in the FB model. In contrast, this combining is explicitly represented in the comparison FCO model by the function "contact staples and sheets". This difference is handled by adding this FCO function of the comparison model to the interim model. The difference between the models regarding the representation of (parts of) users of devices is handled by *removing* FB functions in the model conversion. In the FB model, parts of users are represented in terms of flows of human materials such as "hand". In contrast, parts of users are not represented in the comparison FCO model, nor are they in FCO models of devices in general. The FCO treats (parts of) users as external to devices and therefore does not represent these in functional models of devices. Ookubo et al. [21] handle this difference by removing FB functions that have input or output flows of human materials. In the interim model, for instance, the FB function "import solid (hand)" is removed. The end result of these translations and modifications is the converted FB model (*Cfm1*) in Figure 4. As can be seen, the FCO function "contact staples and sheets" is added to this model, and the FB function "import solid (hand)" is removed from this model.

In the next section it is argued that FB-FCO model conversions, interesting and valuable though they are, lead to problems of information loss.

5. PROBLEMS OF INFORMATION LOSS

5.1. Removing Functional Basis-model features

The second modification step of the conversion methodology shows that incompatible model features between FB models (*fm1*, Figure 1) and FCO models (*fm2*, Figure 2) are handled by *removing* such FB model features. Consider the removal of the FB function "import solid (hand)". Although such a removal resolves incompatibilities, functional information that is represented in the to-be-converted model (*fm1*) is lost in the converted model (*Cfm1*). This removal of FB user features causes information loss [34]. Taking this removal step as a general rule seems the only option available to the conversion methodology for solving other differences with respect to FB model features that are not part of FCO models, i.e., in the stapler example the conceptual differences (2) and (6) that Ookubo et al [21] are currently investigating to solve. Consider the conceptual differences regarding the connectivity of FB functions in terms of flows (2) and the separation of material and energy flows (6) in FB models. When the removal step is not applied, a final converted model then represents features – input-output flow connectivity between functions and separated material and energy flows – that *conflict* with the FCO modelling guidelines for functional model descriptions. In the FCO approach, instead of functions, behaviours of components are connected by input-output operands of material, energy and signal in behavioural models [21]. And material and energy operands are separated in these behavioural models, not in functional models [25]. So, not applying the removal step with regard to the differences (2) and (6) leads to converted models that include features of FCO behavioural models, which conflict with FCO functional models. The removal step thus seems the only option available to the conversion methodology to handle the differences (2) and (6). This unfortunately comes at a price: it leads to extensive information loss of FB model information. Consider for instance the FB model of the stapler in Figure 1. By removing the input-output flow connections between FB functions and by removing the separation of material and energy flows in FB models, key FB model features would be removed in a conversion (moreover, the converted model would then conflict with FB modelling rules, since functions must explicitly be connected by input-output flows and flows must explicitly be separated in the FB account [22]).

5.2. Identifying the Functional Basis-concept of function with the Functional Concept Ontology-concept of behaviour

There is an explanation for the conceptual differences (2) and (6) between FB models (e.g., *fm1* in Figure 1) and FCO models (e.g., *fm2* in Figure 2) and the above dilemma it poses for the conversion methodology. FB-to-FCO model conversions are done under the assumption that the concept of function in the FB approach is (to a large extent) the same as the concept of function in the FCO approach [19,21]. Most FB function terms and all FCO function terms are in the conversion methodology identified as "flowing object functions". It is argued in this paper that this assumption is erroneous. The concept of function adopted in the FB approach differs critically from the concept of function endorsed in the FCO approach. In a nutshell: FB functions correspond to desired physical behaviours and can be identified with FCO behaviours. FCO functions, instead, describe roles of behaviours [13] and correspond to features of physical behaviours.

Firstly, consider the conceptual difference mentioned above of input-output flow connections between FB functions (2). Both functions in FB models and behaviours in FCO behavioural models are connected in terms of input-output of material, energy and signal. Since behaviours are, typically, causally connected, this supports my position that FB functions correspond to desired physical behaviours and have the same meaning as FCO behaviours. FCO function descriptions instead characterize roles that can be attached to physical behaviours. Causal physical input-output connections do not apply to role descriptions in FCO. My next argument shows that such role descriptions correspond to only certain features of physical behaviours.

Secondly, functional descriptions in FB models are modelled in accordance with physical conservation laws for matter and energy [35], whereas functional descriptions in FCO models do not need to be. FCO functions may correspond to only input or output states of behaviour, instead of to an input-output transformation [25]. A role description that is attached to only an input or output behavioural state need not be described in accordance with physical laws, since the role corresponds to only a feature of behaviour. Consider, for instance, the FCO function "consume bonding force of sheets" in Figure 2. Physical laws are not taken into account in this description. If they were, the disappearance of bonding force would instead be represented as a transformation into another form of energy, say heat. In the FCO approach, behavioural models take care of physical laws [13]. Sasajima et al. [25] for instance give the example of the behaviour of a device as dividing an input saline solution into pure salt and a saline solution. The function attached to this behaviour is described as "producing salt". Whereas the behavioural description is given in accordance with conservation laws, these laws are not taken into account in describing the role of this behaviour. The fact that FB functional models are modelled in compliance with physical laws, like FCO behavioural models, further supports my position that FB functions correspond to (FCO) physical behaviours (in [19] and [21] the distinction with respect to conservation laws is not noticed).

Considered from this perspective, the conceptual differences (2) and (6) between FB functional models (*fm1*) and FCO functional models (*fm2*) emerge as differences between *FB behavioural models* and *FCO behavioural role models*. This result immediately explains why these differences emerge between FB models and FCO models in the conversion methodology: these models have a different meaning. It also explains why an adequate solution to solve them is not in view, if the assumption is upheld that the meaning of functions in FB models and FCO models is the same. Under this assumption of sameness of meaning, to avoid incompatibilities between FB models and FCO models, the FB model features of input-output flow connectivity and separation of material and energy flows must be removed in model conversions. As argued, this leads to extensive information loss.

The result that FB models characterize behavioural models and FCO models characterize behavioural role models gives a novel perspective on the FB-FCO model conversions developed by Ookubo et al. [21]. In the current endpoint of their conversion (*Cfm1*, Figure 4), functions are connected by input-output flows, material and energy flows are separated and the model is in accord with physical conservation laws. The converted FB model *Cfm1* thus exhibits all the model features that were identified as features characteristic of behavioural models. I submit therefore that the FB-FCO model conversion in its current version must be understood as *a conversion of an FB behavioural model into an FCO behavioural model*. Interpreting Ookubo et al.'s [21] FB-FCO model conversion in this fashion makes it no less valuable: it establishes the exchange of behavioural knowledge between the FB and FCO taxonomies. Considering the pivotal role played by the concept of behaviour in engineering [16] this result is an important achievement in its own right. The research challenge we now face, however, is how to relate FB behavioural models to FCO behavioural role models. This challenge is taken up in the remainder of this paper. A strategy for addressing this challenge is presented, taking off from the claim that the FB-FCO model conversion developed by Ookubo et al [21] is a behavioural model conversion. It is shown that by taking behavioural model conversions as starting point in this strategy, the problem of information loss is solved.

6. SOLVING PROBLEMS OF INFORMATION LOSS

6.1. Converting behavioural models and abstracting behavioural role models

A two-step strategy is presented to establish knowledge exchange between FB behavioural models and FCO behavioural role models. The strategy developed here incorporates a proposal by Garbacz [36]. Garbacz [36] has developed a logical formalization of functional decomposition in which he defines behaviours as changes of flows and functions as abstracted behaviours. He states that these definitions allow for a reconciling of functional modelling approaches that define functions as abstractions or interpretations of behaviours with functional modelling approaches that define functions in terms of input-output flow relationships. By combining his reconciliatory step of abstracting functions from behaviours with my analysis of the distinction between FB behaviour-functions and FCO behavioural role-functions one can imagine the following solution.

In a first step, FB functions are translated into FCO behaviours. Flow connections between functions and the separation of material and energy flows are converted as well. This step establishes an FB-FCO behavioural model conversion, preserving the model features of input-output flow connectivity and the separation of material and energy flows. (Whereas behavioural models in FCO include all possible behaviours to which a role can be ascribed [26], this set is pruned down in my proposal. Since in my position FB-functions correspond to desired physical behaviours, this gives you the relevant set of FCO behaviours on which to base the abstraction of FCO functions)

In a second step, the relevant features of the behaviours represented in the converted behavioural model are abstracted and incorporated into behavioural role descriptions. These role descriptions are used to develop a behavioural role model. This abstraction step links converted FB behavioural models to FCO-inspired behavioural role models. These translation and abstraction steps preserve functional information concerning flow connectivity and separated material and energy flows, for these features are now characterized in a converted behavioural model. And they allow the linking of (translated) FB behaviour-functions to FCO behavioural role-functions. Both behavioural and functional knowledge exchange can thus be established with this two-step strategy. The models of the stapler in Figures 1, 4 and 5 illustrate my proposal. The FB model in Figure 1 represents the to-be-converted behavioural model (*fm1*) and the converted FB model in Figure 4 represents its converted counterpart (*Cfm1*). The model in Figure 5 represent an FCO-inspired behavioural role model, abstracted from the converted behaviour model (*Cfm1*). This abstracted model has a similar format as the comparison FCO model (*fm2*, Figure 2), except that ways of achievement are not represented. The overall function "combine sheets" is the same as in *fm2*. The functions are represented according to their grouping in function chains and modules in the converted FB model (*Cfm1*, Figure 4). Using the module information of the converted FB model for the grouping of FCO functions in Figure 5 accords with the use of ways of achievements for the grouping of functions in FCO. Ways of achievement refer to information about structures and the behaviours that they exercise. Likewise, modules refer to information about structure and FB-functions to the behaviours they exercise. Module information is given at the nodes (cf. Figure 4). I use oval nodes in Figure 5 to distinguish module information from ways of achievement, which are represented in FCO models by squares (cf. Figure 2).

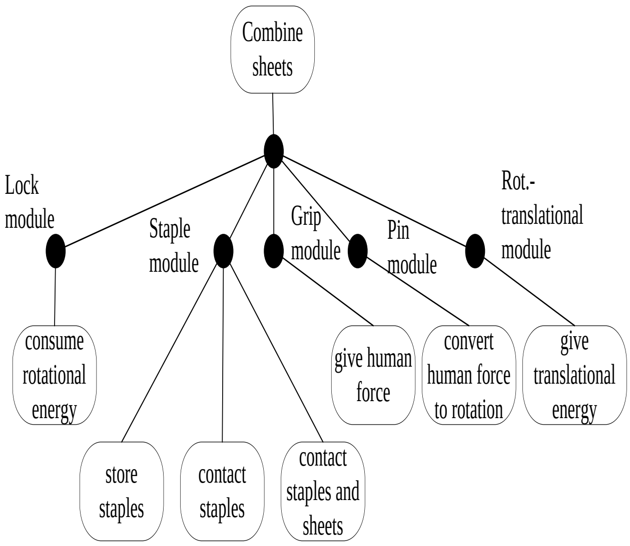

Figure 5 Abstracted FCO-inspired behavioural role model of a stapler

In line with the aim underlying the conversion methodology to establish knowledge exchange between functional taxonomies, this paper presents this alternative as a conceptual tool to address the loss of information in FB-to-FCO model conversions, establishing both behavioural and functional knowledge exchange between these taxonomies. My alternative strategy can be applied both ways. The focus here was on knowledge exchange from the FB taxonomy to the FCO taxonomy. In opposite direction, we can, for instance, take the FCO model of a stapler in figure 2 (*fm2*) as starting point and then develop the FCO behavioural model on which it is based. After construction of this FCO behaviour model, we can subsequently convert it to a FB behaviour model, establishing behavioural and functional knowledge exchange from FCO to FB. (This proposal is not demonstrated here due to space limitations).

6.2. Discussion: generalizing the knowledge exchange strategy

My alternative strategy for establishing knowledge exchange between the FB and FCO taxonomies gives conceptual means for developing a general strategy to establish knowledge exchange between other functional taxonomies.

This general strategy differs from the conversion methodology in the following respect. Whereas the conversion methodology starts with a translation of function terms between taxonomies and then analyses conceptual differences between models of different taxonomies, I reverse these steps. The meaning of function terms in functional taxonomies and meaning correspondences between terms of different taxonomies is in the conversion methodology solely determined by matching definitions of these terms with function categories in the reference ontology [19,21]. Only in the second step of the conversion methodology are conceptual differences between models based on different taxonomies taken into account. Yet, these are not taken as indicative of differences in function meaning. The analysis presented in this paper shows instead that conceptual features of models should be taken into account in fixing the meaning of function terms and conceptual differences between these model-features in specifying differences in function meaning. Focussing solely on matches between function terms and function categories in the reference ontology is a too general procedure: e.g., both FB and FCO function terms are classified in the same function category of “flowing object” functions, despite the fact that the concept of FB function differs in meaning from the FCO concept of function. Therefore this paper submits that a more viable way to establish knowledge exchange is by taking conceptual differences between models of different taxonomies into account from the start.

Taking these steps in this reversed fashion in FB-FCO model conversions seems a promising way for tackling differences between other approaches in model conversions as well. The connectivity between functions, the separation of material and energy and the modelling in accordance with physical conservation laws for matter and energy are features that are highly discriminative between functional modelling approaches in general [27].

Analysing conceptual differences such as the ones above between functional models marks the first step in my strategy. This analysis then subsequently informs what type of translations (and conversions) can be carried out in a second step, e.g., translations of behaviours or behavioural roles (the other meanings that the concept of function has in the engineering domain are here for the sake of simplicity ignored). If the analysis in the first step reveals a difference in the meaning of the concept of function between taxonomies – behaviours vs. behavioural roles – then first a behaviour model conversion is carried out in the second step. After this behavioural model conversion, a behavioural role model is then abstracted. If the concept of function has the same meaning in both taxonomies, a model conversion takes care of knowledge exchange. Depending on the meaning of function adopted in both taxonomies, this can be either a behavioural model conversion or a behavioural role model conversion. This strategy bypasses problems of information loss, such as occurring in FB-FCO model conversions with the conversion methodology. The specific details of such model conversion-cases will, of course, depend on the approaches paired in a model conversion. The strategy proposed here provides a general conceptual framework for developing them. Future work is aimed at investigating these conversions in detail.

7. CONCLUSIONS

This paper reviewed a methodology developed by Kitamura, Mizoguchi and co-workers for the conversion of functional models between functional taxonomies. They apply their methodology to the conversion of functional models described in terms of the Functional Basis taxonomy into functional models described in terms of the Functional Concept Ontology taxonomy. It was argued in this paper that these conversions lead to information loss. Specifically, it was shown that some features of Functional Basis models are incompatible with Functional Concept Ontology models, and that removal of these features is the only option available in these conversions for resolving incompatibilities. An alternative strategy is then presented for solving this information loss. It is shown that model conversions are carried out under the assumption that the meaning of the concept of function in the Functional Basis and the Functional Concept Ontology is the same. It is argued instead that the meaning of the concept of function between these taxonomies differs. The incompatibilities between Functional Basis models and Functional Concept Ontology models were explained in terms of this difference. It was argued that Functional Basis-functions correspond to desired physical behaviours whereas Functional Concept Ontology-functions correspond to roles of behaviours. Based on this distinction, a two-step strategy is presented that is able to retain Functional Basis information. Firstly, Functional Basis-functional models were converted into behavioural models. Secondly, behavioural role models were abstracted from converted behavioural models. It was concluded that this strategy supports the establishment of behavioural and functional knowledge exchange between the Functional Basis and Functional Concept Ontology taxonomies without information loss. It is suggested that the alternative strategy proposed in this paper for establishing knowledge exchange between the Functional Basis and Functional Concept Ontology taxonomies generalizes to establishing knowledge exchange between other functional taxonomies as well. Specifically, the conceptual features of models that were taken into account in fixing the meaning of Functional Basis and Functional Concept Ontology function terms, and conceptual differences between these model-features are highly discriminative between functional modelling approaches in general. Future work is aimed at developing conversions of functional models between other functional modelling approaches.

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