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MODELLING FUNCTIONS AS OPERATIONS ON MATERIAL, ENERGY AND SIGNAL FLOWS: CONCEPTUAL PROBLEMS AND POSSIBLE SOLUTIONS

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ABSTRACT

In this paper I review the modelling of functions of technical products as operations on flows of materials, energies and signals. This modelling is increasingly accepted as a tool for conceptual designing in the mechanical and electromechanical domains, and is extended to new domains and used for additional goals. After presenting the modelling I discuss five problems and their possible solutions. The review is conceptual and focuses on general assumptions in the modelling; the discussion of solutions is theoretical and sketches how the modelling may develop. The discussed problems include (i) ambiguous use of the term function, (ii) a difficulty in translating overall product functions into operations on flows, and (iii) the adoption of elementary subfunctions that are technologically hardly elementary. Possible solutions include recent proposals for improving the modelling. I argue that these proposals make the modelling more flexible: operations-on-flows are not anymore associated with one monolithic notion of function (problem iv) but can represent primary functions, subsidiary functions and behaviour; and artificial distinctions between material, energy and signal flows (problem v) can be overcome. The paper focuses primarily but not exclusively on the functional basis account by Robert Stone and Kristin Wood.

KEYWORDS

functions, functional modelling, functional basis, functional decomposition, behaviour

1. INTRODUCTION

In this paper I review the modelling of functions of technical products as operations on flows of materials, energies and signals. This modelling has been around for a number of decades and has gained acceptance in engineering through, for instance, the design methodology of Gerhard Pahl and Wolfgang Beitz (1977) and current ongoing research on the functional basis account by Robert Stone and Kristin Wood (2000). Briefly put, the modelling allows overall product functions to be decomposed into sets of connected elementary subfunctions. An 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 subfunction is also described in a verb-object form but represented by a well-defined basic operation on well-defined basic flows of materials, energies and signals. The black-boxed operation on general flows representing a product function is derived from costumer needs, and the basic operations and basic flows representing subfunctions, are laid down in common libraries that span the functional design space. Stone and Wood call these libraries a *functional basis*.

The modelling of functions as operations on flows is presented as a tool for supporting the conceptual phase of engineering designing in the mechanical and electromechanical domains. Yet, it is increasingly extended to new domains and used for other tasks. The modelling is also applied to, for instance, the domain of manual processes (Nagel et al., 2006; 2007b). And additional tasks are archiving, the comparison and communication of functional descriptions of existing products (Stone and Wood, 2000), and the creation of ontologies for product components (Bryant Arnold, 2007).

The review in this paper is general and conceptual. I critically analyse the meaning and the use of key terms, and evaluate general assumptions in the modelling by considering whether they are applied consistently and whether they make sense for all cases to which the modelling reasonably applies. This review leads to the identification of five problems. The discussion of possible solutions to these problems is theoretical rather than one that leads to empirically corroborated alternatives. In this discussion recent proposals from the literature to improve the modelling are considered and used for sketching how the modelling may develop.

After presenting the main elements of the modelling in section 2, I present in section 3 the five problems:

(i) the term function is used ambiguously;
(ii) verb-object descriptions of product functions translate not always into operations on flows;
(iii) elementary subfunctions need not be technological elementary;
(iv) operations-on-flows need not always represent functions;
(v) separating flows through products in material, energy and signal flows seems artificial.

In section 4 I describe possible solutions to these problems drawn from an earlier analysis of the work of Stone and Wood (Vermaas, 2007) and from recent work in the literature. The ambiguity (i) is solved by using the term function for one meaning only. Problem (ii) may be avoided by explicitly taking into account the choice of system boundaries of products. Problem (iii) points towards making a distinction between elementary subfunctions that are defined by functional bases and subfunctions that are technologically elementary by being readily solvable in designing. With regard to the remaining problems a number of recent proposals is reviewed in which distinctions are made between types of functions represented by operations on flows. It is argued that these proposals may make the modelling more flexible in two ways. First, addressing problem (iv), operations-on-flows do not represent anymore one monolithic notion of function, but may refer to functions that are *primary* in the sense of contributing directly to the overall product function, to functions that are *subsidiary* in the sense of being needed for supporting primary functions, and even to *behaviour* that does not count as functional at all. Second, addressing problem (v), these proposals may rid the modelling of the systematic distinction between material, energy and signal flows.

The review focuses primarily but not exclusively, on the functional basis account of Stone and Wood since much of the current research on the modelling of functions as operations on material, energy and signal flows, is done within the context of that account. The review, especially the description in the next section, builds on (Vermaas, 2007).

2. MODELLING FUNCTIONS

2.1. Decomposing functions

The functional basis account of Stone and Wood (2000) supports, as said, the designing of new products since it allows designers to represent overall product functions and to decompose these functions early in the design process into sets of connected elementary subfunctions. These subfunctions are moreover supposed to be ‘small, easily solvable subfunctions’, i.e., subfunctions for which solutions exist, such that ‘the [structural] form of the [product to be designed] follows from the assembly of all sub-function solutions’ (2000, §3.1). Stone and Wood introduce their account in terms of the tasks designers have to carry out when applying the account. A coarse-grained description of these tasks is as follows.

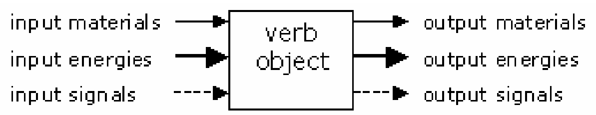

Figure 1 Representation of a product function or subfunction

The first task is to arrive at an overall product function of a product to be designed, described in a *verb-object form* and represented by a *black-boxed operation* on flows of materials, energies and signals (see Figure 1). The black-boxed operation originates from customer needs and may initially be quite general and is refined later on in the design process. Thus, in terms of Stone and Wood’s example of a hot air popcorn popper (see Figure 2, adopted from Stone and Wood (2000, fig. 7)), initially the input flow of materials contains corn kernels, the output flow of material contains popcorn, and the rest of the flows are left unspecified. Later on in the design process

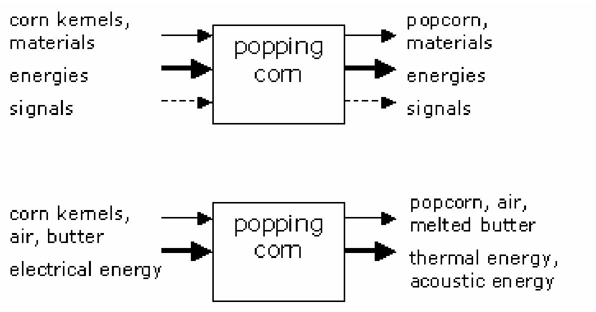

Figure 2 Initial and final representation of the overall product function of a popcorn popper

the input is defined as corn kernels, butter, air and electrical energy, and the output as popcorn, melted butter, air, thermal energy and pneumatic energy. The verb-object description of the product function and its operation-on-flows representation are related as follows: the verb corresponds to the operation, and the object corresponds to (parts of) the flows. For instance: the function of the popcorn popper is ‘popping corn’ such that the initial input and output flows consist of ‘corn’, and the operation is one of ‘popping’.

Table 1 Library of basic operations; Hirtz et al. (2002)

primary functions	secondary functions
branch	separate
	distribute
channel	import
	export
	transfer
	guide
connect	couple
	mix
control magnitude	actuate
	regulate
	change
	stop
convert	convert
provision	store
	supply
signal	sense
	indicate
	process
support	stabilize
	secure
	position

The second task is to define for each input flow a chain of subfunctions that transforms that flow step-by-step into (parts of) the output flow. These subfunctions are also described in verb-object forms and represented by operations on flows. But now the verbs are to be chosen from a fixed library of operations, called *basic functions*, and the flows are to be chosen from a fixed library of basic flows. The two libraries make up the functional basis and are listed in Tables 1 and 2, respectively (they are the improved libraries given in Hirtz et al. (2002); the third level of tertiary functions and flows is not included). The subfunctions part of the different chains must be ordered in time with respect to one another.

The third task is that these temporally ordered chains of subfunctions are integrated by connecting the chains, thus arriving at the decomposition of the overall product function. For the popcorn popper a part of its functional decomposition is given in Figure 3 (it is the energy-flow part, adopted from Stone and Wood (2000, fig. 7), with verb-object names adjusted to the improved libraries of Hirtz et al. (2002); the energy arrows at the right-hand side pointing to the right are output flows, the energy arrows at the bottom pointing downwards and upwards are internal flows to and from the other chains of subfunctions). Figure 4 (adopted from Bryant et al. (2006, fig. 1)) gives a full functional decomposition, now of the overall product function ‘hold liquid and retain heat’ of a cup.

The designer thus has to analyse the input flows of the overall function in terms of basic flows from the library of basic flows, and has to come up with a series of operations from the library of basic operations that sequentially and/or in parallel transforms the input flows step-by-step into basic flows that, together, make up the output flows.

Table 2 Library of basic flows; Hirtz et al. (2002)

primary flows	secondary flows
material	human
	gas
	liquid
	solid
	plasma
	mixture
signal	status
	control
energy	human
	acoustic
	biological
	chemical
	electrical
	electromagnetic
	hydraulic
	magnetic
	mechanical
	pneumatic
	radioactive/nuclear
	thermal

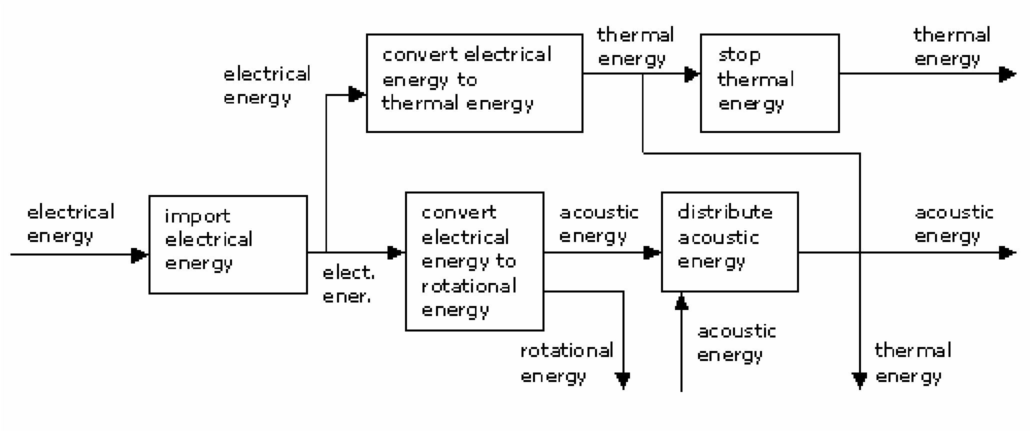

Figure 3 Part of a functional decomposition of ‘popping corn’; Stone and Wood (2000, fig. 7)

2.2. Finding design solutions

Further examples of functional decompositions of product functions can be found at a web-based repository (http://function.basiceng.umr.edu/delabsite/repository.html). This repository stores the decompositions of product functions of existing products, and stores their components as design solutions for the various subfunctions part of these decompositions. At this site one can moreover find an automated mathematically-based design tool called the *Concept Generator*. This tool is aimed at creating new decompositions for any overall product function that is fed into it, and at generating design solutions for these overall product functions on the basis of the design solutions for subfunctions that are already stored in the repository. The Concept Generator solves a part of problem (iii) with modelling functions as operators on flows (see section 4.3). I therefore introduce the algorithm used by the Concept Generator to generate design solutions (Bryant et al., 2006, §3). This introduction is again coarse-grained, describing what the algorithm does, but ignoring the means by which it does so.

In the first step of the algorithm, the Concept Generator translates a decomposition of the overall product function (only models consisting of single chains of subfunctions are considered in Bryant et al. (2006)) into information about the subfunctions and their adjacency. Secondly, the Concept Generator collects for each individual subfunction in the chain design solutions consisting of components that are stored in the repository as having that specific subfunction. In the third step all design solutions for the product as a whole are generated by describing on the basis of the information gathered in the first two steps all theoretically possible component chains that solve the overall product function. Fourthly, additional information is collected from the repository about which sets of components have been actually combined in existing products, and can in that sense can be taken as sets of technologically compatible components.

Finally, in a fifth step, this information about the

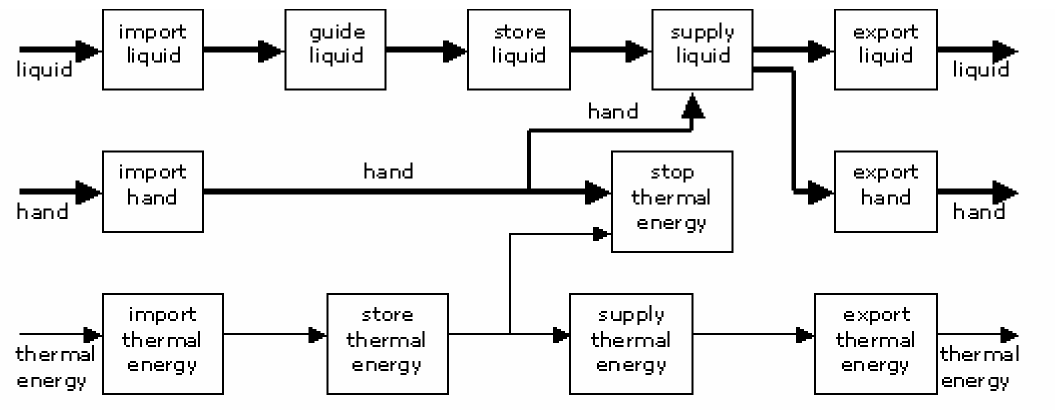

Figure 4 A functional decomposition of ‘hold liquid and retain heat’; Bryant et al. (2006, fig. 1)

compatibility of components is used to prune the set of theoretically possible component chains to a set of feasible component chains. In this final step also a ranking is added to these feasible chains, aimed at "bubbl[ing] the most promising solutions to the top." I here ignore how this ranking is produced; the point relevant in this paper is that the algorithm puts constraints on the decompositions of overall product functions: the algorithm allows only for decompositions that consist of subfunctions for which there are components stored in the design repository that have these subfunctions.

3. CONCEPTUAL PROBLEMS

I assume in this paper that the continuing engineering interest in modelling functions in terms of operations on flows proves the versatility and usefulness of this modelling, thus clearing the way to review it from a primarily conceptual point of view. In this section I present five problems this review leads to. In the next section I then broaden the discussion to possible solutions.

3.1. Two meanings of *function*

A first problem is a terminological one, and concerns the use of term 'function' in the modelling. This term refers typically to both the *entities represented* by operations on flows, and to the *operations* used in the representations. Stone and Wood, for instance, define 'function' as "a description of an operation to be performed by a device or artifact, expressed by the active verb of the sub-function" (2000, §2). The basic operations as defined by the functional basis (see Table 1) are thus functions, as is also expressed by the headings 'primary' and 'secondary function' to categorise the operations. Functions refer thus to *operations*, such as 'popping' or 'storing'. Yet, Stone and Wood also use the notions of 'product function' and 'subfunction' ('subfunction' is even part of the definition of 'function') and these two notions do not fit the definition of function. Product functions and subfunctions are separately defined by Stone and Wood (2000, §2), and according to these definitions they are expressed by verb-object forms, capturing the tasks of products or of their components, respectively. Product functions and subfunctions are thus referring to things like 'popping corn' or 'storing thermal energy.' Product functions are therefore not merely *operations*, but represented by operations-*on-flows*, which warrants the somewhat awkward conclusion that, strictly speaking, product functions and subfunctions are not functions.

The same ambiguity is present in the work by Pahl and Beitz on functional decomposition in designing (2007, §§2.1.2-2.1.3). Pahl and Beitz also use a list of basic operations – a different one than Stone and Wood's, and consisting of *change*, *vary*, *connect*, *channel* and *store* (2007, fig. 2.7) – and call these basic operations 'generally valid functions'. A 'function' of a system is, moreover, characterised by Pahl and Beitz as the "intended input/output relationship" of the system (2007, §2.1.2), which may be read as again singling out only the (intended) operation that maps the input to the output. Yet, in the same section Pahl and Beitz also write that "[f]unctions are usually defined by statements consisting of a verb and a noun, for example "increase pressure" […]", leading to the conclusion that for them the term function also can refer to operations-on-flows.

(In this paper I use 'function' only to refer to that what is represented by operations on flows.)

3.2. Verb-object characterisations of product functions without natural operations-on-flows representations

The second problem concerns the relationship between the operations-on-flows representation of functions and their verb-object ('verb-noun' for Pahl and Beitz) characterisation. As said in section 2.1, Stone and Wood take it that the verb corresponds to the operation and the object corresponds to (parts of) the flows: the 'popping corn' function is thus represented by a black-boxed operation 'popping' on flows that include 'corn'. Two examples challenge this straightforward relation between the verb-object characterisation and the operations-and-flows representation. Consider the function 'cooling human body' of an electric fan (adopted from Kitamura et al. (2007)) and the function 'detecting planes' of radar (given in (Vermaas, 2007)). Application of the mentioned relation yields that these functions are represented by the operation 'cooling' on an input-output flow consisting of 'human bodies', and the operation 'detecting position' on a flow of 'planes', respectively. Yet, from an engineering point of view, human bodies do not enter or leave electric fans, and neither do planes go through radar installations. The proper way of representing these functions as operations on flows is by, say, 'convert electrical energy to a flow of air' for the fan and 'convert electrical energy to signals that reveal plane positions' for radar. Hence, for some product functions the relationship between verb-object characterisation and their operations-on-flows representation is more complex that assumed: verbs in the characterisation need not correspond to the operations in the representation and the objects need not correspond to the flows.

Note that this second problem is caused by the conjunction of three assumptions: (i) functions have verb-object characterisations, (ii) functions can be represented by operations on flows, and (iii) the verbs are corresponding to the operations, and the objects are corresponding to (parts of) the flows. Together these assumptions lead to the conclusion that human bodies are to be taken as flowing through fans and that planes flow through radar installations. Yet, this conclusion need not immediately be taken as reason for rejecting the second assumption, which is central to the modelling of functions as operations on flows. This assumption (ii) can still be accepted together with the position that (i) functions have verb-object characterisations, as soon as one gives up the third assumption (iii), as I will do in section 4.2.

3.3. Technologically non-elementary subfunctions

A third problem concerns the idea that the subfunctions into which overall product functions are decomposed are from an engineering point of view *elementary*. Stone and Wood are quite explicit that the subfunctions defined by their functional basis are "small, easily solvable subfunction[s]" in designing. And more in general it is assumed in the literature that these decompositions help designing because engineers have for all subfunctions design solutions available.

A brief look at the libraries of the functional basis defined by Stone and Wood, seems to confirm this assumption: for each primary and secondary 'function' in Table 1 a quick design solution may come to mind. But this confirmation trades on the ambiguity discussed in section 3.1: the primary and secondary 'functions' of Table 1 are actually basic operations and not the subfunctions into which product functions are decomposed. Hence, regardless of whether these basic operations may seem 'small and easily solvable', what actually has to be established is that there is a design solution for each subfunction defined by applying a basic operation from Table 1 on some basic flows of Table 2. The functional basis generates many of such *basic-operations-on-basic-flows* combinations and it can be argued that they are not all representing small and easily solvable subfunctions. Consider, for instance, the combinations 'convert hydraulic energy to nuclear energy,' and 'join plasma and solid.'

More generally one can argue that the notion of a small and easily solvable subfunction and the notion of a subfunction represented by a basic-operation-on-basic-flows need not coincide. Some of the latter combinations are according to the above not easily solvable. And conversely there are subfunctions that are small and easily solvable in engineering, but that are not represented by one basic-operation-on-basic-flows combination. Consider, for instance, the subfunction 'hold liquid and retain heat.' According to Bryant et al. (2006) this subfunction is composed of twelve subfunctions as defined by the functional basis (see Figure 4) and thus not represented by one basic-operation-on-basic-flows. Yet, this subfunction is easily solvable: a single cup will do the trick.

Another way in which the notions of a 'small-and-easily-solvable subfunction' and a 'subfunction represented by a basic-operation-on-basic-flows' differ, is in their dependence on technical context. The set of subfunctions represented by basic-operations-on-basic-flows is independent of context but fixed once the libraries of basic operations and basic flows are fixed. Yet, the set of small and easily solvable subfunctions does depend on context in at least two ways. First it depends on the abilities of engineers, and thus changes when the state of the art in technology develops. 'Convert electrical energy to rotational energy is nowadays by the availability of electric motors an easily solvable subfunction. But for designers working two hundred years ago this subfunction was rather one without solutions. Second the set of small and easily solvable subfunctions may be deliberately made smaller in certain design tasks. If designers are working on a new type of electric engine, they will not take the subfunction 'convert electrical energy to rotational energy' as an easily solvable one; such designers are rather facing the task of breaking up this subfunction into other subfunctions they do take as easily solvable.

3.4. Non-functional operations-on-flows

Fourthly it can be argued that decompositions of overall product functions may define basic-operations-on-basic-flows that do not represent subfunctions. Consider, for instance, the decomposition of the overall function of the hot air popcorn popper as given by Stone and Wood (in

Figure 3 the relevant part of that decomposition is displayed). In this decomposition all kinds of subfunctions are defined that concern the flow of energies through the popper, and for meeting the relevant conservation laws, these energy flows are tracked up till the point that they leave the popper as output flows. For this reason the decomposition also contains an operation on energy flows called 'distribute acoustic energy' (the verb-object description of this element is actually 'dissipate acoustic energy' in Stone and Wood (2000) but in the functional basis of Hirtz et al. (2002) 'dissipate' became 'distribute'). It can, however, be doubted whether this operation on flows represents a subfunction that is part of the overall product function of the popcorn popper. Assume, for instance, that the customers and designers concerned do not have specific wishes concerning the noise that popcorn poppers produce. The acoustic energy flow in the functional decomposition is then rather a flow of irrelevant noise, and the distribution of this noise is not corresponding to a task set by someone but merely unintended behaviour within the popper.

This point can be put more general. For capturing an overall product function of a product, such as a popcorn popper (see Figure 2), representing intended flows seems sufficient – costumers needing a popcorn popper may be interested merely in the transformation of corn kernels into popcorn. What happens in functional decomposition is that all kinds of additional flows are included in the representation of the overall function – flows of electricity, butter, and noise, in the case of the popper – although it is unclear whether they are all equally relevant for capturing the overall function. Some of those additional flows and some operations on them are deliberately added by the designing engineer, say because they are from a physical or technical point of view necessary contributions to the overall product function – the flows of electricity and butter in the popper are in this sense necessary and thus an intended part of the functional decomposition of the overall product function of the popper. Other additional flows and operations may come in because they are the result of unavoidable physical and technical processes, even though they do not contribute to the overall product function and are in that sense irrelevant – the noise and the distribution thereof in the case of the popper, for instance. These latter flows and operations seem to merely correspond to *non-functional* behaviour of products, yet are in functional decompositions representing proper subfunctions.

3.5. Artificial separations of flows

A final problem in the modelling of functions as operations on flows is the somewhat artificial distinction between material flows, energy flows and signal flows. Already Pahl and Beitz (2007, §2.1.2) note that these flows are not independent from one another because, for instance, flows of materials and flows of signals cannot occur without accompanying flows of energies. Yet, despite this relationship, and its relevance to engineering, flows of materials, energies and signals are separated in the modelling. Moreover, flows that from a physical point of view seem not to fit in one of these three main types are stipulated to be so anyhow. Force is, for instance, included as subclass of 'mechanical energy' and the electromagnetic field is included as subclass of 'electromagnetic energy'.

This artificial and sometimes unphysical categorisation of flows may be warranted by pragmatic reasons, but is at the same time not unavoidable. Modarres and Cheon (1999, table 1) proposed a library of flows for the modelling of functions, in which the main categories are in addition to mass, energy and information, *momentum*, *force*, *charge* and *electromagnetic wave*.

4. POSSIBLE SOLUTIONS

Identifying solutions to the five problems presented is not only of interest for finding ways to improve on the modelling of functions as operations on flows. These solutions also point to a development that may make this modelling more flexible: operations-on-flows may in the near future come to represent different types of functions and possibly even non-functional behaviour; and the flows concerned need not anymore be strictly separated in material, energy and signal flows.

4.1. One meaning of 'function'

For removing the ambiguity in the meaning of the term function it seems that we just have to make a choice: will we use this term for referring to that what is represented by operations-on-flows, or will we use it for referring to the operations themselves? Intuitions about what functions really are in engineering will presumably not help with making this choice, since these intuitions may be ambiguous themselves. The operations themselves certainly have a functional character. They work like mathematical functions since operations may be seen as generalised maps defined over the domain of all (relevant) flows, just like mathematical functions are defined as maps over specific domains. The operations-on-flows are in contrast ordered relations that link one particular input to one particular output. An argument that I can bring up to reserve the term 'function' in engineering to that what is represented by operations-on-flows, is that one then can stick to the habit of including the inputs and/of outputs in the description of functions of products: the function of the popcorn popper is then "popping corn" and not merely "popping". Furthermore, with this choice one avoids that technologically rather different functions become lumped together as one and the same: 'convert petrol to propulsion' and 'convert electricity to pulsed monochromic light' are then two different functions and not instances of the same 'convert' operation.

4.2. Scalable system boundaries relating verb-object characterisations and operations-on-flows representations

Let us accept the assumptions that (i) functions have verb-object characterisations, and that (ii) they can be represented by operations on flows. Then, in order to avoid the conclusion that in the modelling of the functions of fans and radar, human bodies are flowing through fans and planes through radar installations, one has to reject the third assumption (see section 3.2) that (iii) the verbs in the characterisations of functions correspond to the operations in the representations of those functions, and that the objects correspond to (parts of) the flows.

This rejection raises the question of how the relation between the verb-object characterisations of functions and their operations-on-flows representations is to be understood. I do not have a general answer available but will argue that the scaling of system boundaries of products plays a role in the relation. In brief it seems that the problem is that the verb-object characterisations of product functions may be capturing the effects of products on their environment, whereas the operations-on-flows representations of product functions focus on what is happing within the products. If this is so, the relation between the two consists of a link between the effect of a product on its environment and that what happens within the product.

Consider again the electric fan and the radar installation with the product functions 'cooling human body' and 'detecting planes'. The effects that these products have on their environment may actually be captured by operations on flows, where the operations correspond to the verbs, and the flows to the objects. The effect of the fan can be taken as 'separate thermal energy from a human body flow' and the effect of radar can be taken as 'sense positions of plane flows.'

In the case of radar the operation-on-flows representation of its effect may actually be taken as representing a product function, although not of the product function of the radar installation itself. One can speak of a radar *system* or a radar *network* (this is certainly done when one has a series of radar installations) when taking the system boundary of the radar installation wide enough that it includes the area scanned. The planes indeed are going through this area, such that one can maintain that this radar *system* has the product function represented by the operation-on-flows 'sense positions of plane flows.' The product function of the radar *system* can now be connected with the product function of the installation itself by scaling down the system boundary to that installation. And this scaling down seems to correspond to a functional decomposition of the radar *system*'s product function 'sense positions of plane flows' into subfunctions that include the product function of the radar installation represented by, say, 'convert electrical energy to signals that reveal plane positions.'

In the case of the electric fan we do not have a term for referring to the 'fan *system*' one obtains by taking the fan's system boundary wide enough to include the human body that it cools. Yet the relation between the verb-object characterisation of the fan's product function and the operation-on-flows representation of this function can be made similarly as in the radar case. By considering the wide system boundary, the verb-object characterisation of the fan's product functions can be translated into an operation-on-flows representation of the fan's effect on its environment, where the operation corresponds to the verb, and the flows to the object. And by decomposing this operation-on-flows of the effect one obtains the operation-on-flows representation of the fan's product function. This last representation is something like 'convert electrical energy to a flow of air,' and focuses on what happens within the fan when its system boundary is scaled down.

4.3. Adding technologically elementary subfunctions

The problem that a functional basis may define basic-operations-on-basic-flows subfunctions that are technology not elementary is actually solved by the Concept Generator algorithm. This algorithm (see section 2.2) selects from all possible functional decompositions of a product function only those that are made up of basic-operations-on-basic-flows subfunctions for which design solutions are stored in the repository. Hence, decompositions that contain technologically non-solvable basic-operations-on-basic-flows subfunctions, such as ‘convert hydraulic energy to nuclear energy,’ are filtered out.

Let us therefore focus on the problem that with a functional basis, product functions and subfunctions that are technologically small and easily solvable, may be decomposed into clusters of basic-operations-on-basic-flows subfunctions that are individually not or less easily solvable. Can the Concept Generator, or extensions thereof, also solve this second problem? I believe it may be defended that the answer is positive. One can envisage a search algorithm that identifies such clusters of basic-operations-on-basic-flows subfunctions within functional decompositions and replaces these clusters with the original small-and-easily-solvable subfunctions. If this replacement is done before the Concept Generator compares the subfunctions in functional decompositions with design solutions stored in a repository, then the proper design solutions for these small-and-easily-solvable subfunctions are identified immediately. So, to give an example, functional decompositions of product functions in terms of basic-operations-on-basic-flows subfunctions may be screened for containing clusters of the twelve basic-operations-on-basic-flows subfunctions that make up the small and easily solvable subfunction ‘hold liquid and retain-heat’ (Figure 4). These clusters in functional decompositions, when found, are then replaced by the subfunction ‘hold liquid and retain heat,’ such that a cup comes up as a design solution when the subfunctions in the modified functional decompositions are compared with design solutions stored in the repository.

More generally one can add the set of small-and-easily-solvable subfunctions as a separate ingredient to functional bases. The first problem that the functional basis may define basic-operations-on-basic-flows subfunctions that are not technology elementary, can then be solved directly by requiring that functional decompositions of product functions may not contain basic-operations-on-basic-flows subfunctions that are not elements of this set. And the above sketched search algorithm solves the second problem that small-and-easily-solvable subfunctions may be decomposed into clusters of basic-operations-on-basic-flows subfunctions. The process of functional decomposition becomes in this way sensitive to the tasks designers in different historical and/or engineering contexts face. For engineers who worked two hundred years ago or who are nowadays creating modern engines, for instance, the subfunction ‘convert electrical energy to rotational energy’ is then acknowledged not to be small and easily solvable, and does thus not occur in the functional decompositions these engineers may generate in their work.

The ultimate consequence of adding context dependent sets of small-and-easily-solvable subfunctions to functional bases is that these bases become tailor-made to the design tasks at hand and to the designers involved. This ‘individualisation’ may cohere with the view that designers ultimate solve design problems on the basis of their own personal experience (e.g., (Gero 1990)) but is possibly of less value to the other purposes for which the modelling of functions as operations on flows is proposed. For communicating functional structures of existing products, it may be informative to describe this structure in subfunctions that are considered to be small and easily solvable by the engineers that designed those products. For archiving and comparison of functional structures of products decompositions of overall product functions into context-independent basic-operations-on-basic-flows subfunctions may be preferred.

4.4. Behavioural operations on flows

The problem that decompositions of overall product functions may define basic-operations-on-basic-flows that represent unintended behaviour instead of subfunctions, may be solved by assuming that operations-on-flows represent behaviour in the first place (see also Chandrasekaran (2005) and Garbacz (2006)). Some of these represented behaviours may then be functions by being behaviours that are intended by users or designers. In this way all functions are still represented by operations on flows, but not all operations-on-flows need to represent functions. Returning to the popcorn popper: the by the engineer intended transformation of corn kernels, butter, air and electricity into popcorn (see Figure 2) is then behaviour of the popcorn popper that corresponds to its overall product function; yet the production of melted butter, air, warmth and noise is corresponding to non-functional behaviour. And similarly: the ‘distribute acoustic energy’ operation-on-flows in the functional decomposition of the popcorn popper (see Figure 3) represents a behaviour, but not necessarily a subfunction.

This solution may seem to be a substantial departure from the modelling of functions as operations on flows if one focuses on the work of Stone and Wood (2000), since in that work all operations on flows represent one monolithic notion of function. In other work on modelling functions as operations on flows there is, however, already a tendency to distinguish between different kinds of operations on flows. This tendency can, moreover, be found also in recent work on the functional basis account of Stone and Wood.

Pahl and Beitz (2007, §§2.1.2-2.1.3) distinguish a *main flow* in modelling functions from other flows, and distinguish *main functions* from *auxiliary functions*. If, say, a signal flow is the main flow, then the unavoidable accompanying energy flow is not. And main functions are “subfunctions that serve the overall [product] function directly”, while auxiliary functions are subfunctions “that contribute to [the overall product function] indirectly” and “have a supportive or complimentary character”.

Nagel et al. (2007a) propose to make a similar distinction in the functional basis account of Stone and Wood, but call Pahl and Beitz’ main flow the *primary flow* and distinguish it from *carrier flows* that transport the primary flow.

Modarres and Cheon (1999, §4) take *functions* explicitly as intended behaviours and contrast them with *unintended behaviour* and describe both functions and unintended behaviours in terms of operations on flows.

Hutcheson et al. (2007a,b) extend the functional basis account of Stone and Wood from the modelling of functions to the modelling of behaviours, where modelling of behaviours seems to add to functional modelling quantitative measures to the input and output flows, as well as mathematical relations between these quantified input and output flows.

Hence, also work on modelling functions as operations on flows in the tradition of Stone and Wood (2000) is developing towards a direction in which these operations on flows may represent different types of functions and even non-functional behaviours.

4.5. Technological flows

A solution to the artificial separation of input and output flows into material, energy and signal flows may be to just drop this distinction and opt, for instance, for the physically more reasonable list of flows of Modarres and Cheon (1999, table 1). This would certainly have the advantage that in addition to materials, fields are taken as separate flows (which seems correct from a physical point of view) and that force is not taken as energy (which seems physically also better). Yet also with this alternative list energy is still treated artificially as a flow separate to the material, field and signal flows.

Another way of dealing with the artificial separation of material, energy and signal flows may be found in the mentioned work by Nagel et al. (2007a). In addition to introducing the distinction between primary and carrier flows, they seem to propose the convention in the modelling of functions to group together the carrier flows and the primary flow these carrier flows transport (see for instance Nagel et al. (2007a, fig. 3 and 4)). This convention implies that a signal flow that is taken as primary is always grouped with the accompanying carrier energy flow. In this way artificial separated material, energy and signal flows are recombining to single flows, which, from a technological point of view, were inseparable anyway.

5. CONCLUSIONS

In this paper I have given a general and conceptual review of the modelling of functions as operations on flows of materials, energies and signals. Five problems were raised and for each of them I discussed possible solutions. The nature of the review makes that these solutions are primarily theoretical and explorative; the empirical question of whether engineers perform better when these solutions are incorporated in the modelling, is a question that is not addressed in this paper. This lack of empirical support may be seen as a defect of the review. Conversely, it can be interpreted as due to a division of labour that naturally occurs when a modelling such as the one reviewed is developing and increasingly applied to different domains for different goals: in addition to empirically testing the modelling, it then becomes also of interest to analyse its underlying conceptual framework and explore ways in which this framework may be developed and be attuned to the wider uses of the modelling.

The solution to the first problem – the ambiguity in the meaning of the term function – consists of the proposal to favour one meaning over the other and I have given some support to let functions refer to that what is represented by operations on flows, instead of to the operations themselves.

The second problem that some verb-object characterisations of product functions do not translate straightforwardly into operation-on-flows representations, was in part solved by sketching an alternative relation: the verb-object characterisation of a product function can be taken as the effect of the product on its environment and be represented by an operation-on-flows, where the operation corresponds to the verb in the characterisation, and (parts of) the flows to the objects; by decomposing this operation-on-flows representation of the product's effect – and this decomposition corresponds to scaling down the system boundary of the product from the environment to the product itself – one obtains the operation-on-flows representation of the product function.

The third problem that the elementary *basic-operations-on-basic-flows* subfunctions defined by functional bases, need not be technologically elementary subfunctions, was solved by enriching the modelling and decomposition of product functions with a set of subfunctions that count as small-and-easily-solvable. It was assumed that an algorithm exists that can screen and modify functional decompositions such that it contains these small and easily solvable subfunctions.

In the discussion of the fourth and fifth problem a number proposals for improvements of the modelling of functions as operations on flows were presented. I argued that by these proposals the modelling may become more flexible in two senses that may solve eventually these two last problems. First, operations-on-flows are increasingly taken as not representing one monolithic notion of function, but as referring to functions that are primary (*main functions* in Pahl and Beitz's terminology) in the sense of being directly required by designing engineers, to functions that are subsidiary (*auxiliary functions* for Pahl and Beitz) in the sense of being needed for supporting primary functions, and even to behaviours that do not count as subfunctions at all. Second, these proposals may recombine material, energy and signal flows and, as such, define flows in the modelling that are technologically more natural. This last argument leads to a promissory note: the modelling of functions as operations on flows will in the near future become richer and more sophisticated, and thus pair its success en growth in engineering with the conceptual improvement.

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