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THE FLEXIBLE MEANING OF FUNCTION IN ENGINEERING

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ABSTRACT

In this paper I explain the co-existence of different approaches towards understanding functions. First it is argued that full descriptions of technical devices contain five key concepts: *structure*, *behavior*, *function*, *action*, and *goal*. Then it is shown that such full descriptions can be simplified. Physicochemical descriptions of devices link structure, behavior, and functions, and cloak references to actions and goals. Intentional descriptions link goals, actions, and functions, and cloak behavior and structure. Descriptions that directly link goals of users to the structure of devices, by-pass references to actions and/or behavior. Third it is argued that these simplifications affect the meaning of the concept of function. Functions may refer to desired behavior of devices, to desired effects, or to goals of agents. Function thus has a flexible meaning in engineering that depends on the way full descriptions of devices are simplified. Finally it is shown with three examples that approaches towards understanding functions advance different simplifications. Hence, they co-exist because they represent simplifications of full descriptions of devices that are all valuable to engineering.

Keywords: Function, goal, action, behavior, structure

1 INTRODUCTION

Determining the single meaning of the concept of function in engineering descriptions of technical devices seems currently a project that is bound to fail. In the engineering literature one can find ample reasons for taking up this project. It is often noted that there are different approaches in engineering towards understanding functions that attach also different meanings to this concept. Hence, if a single meaning can be determined, ambiguity and misinterpretation in human and automated communication and storage of functional descriptions can be avoided. Yet, in that same literature these different approaches in understanding functions typically are considered as existing side-by-side rather than as being in competition. Contributions to the literature in which proponents of one approach attempt to disprove other approaches are rare, and certainly outnumbered by contributions in which different approaches are related. A project to determine the single meaning of the concept of function may therefore easily end up in adding merely another approach to the already existing ones, thus enriching the spectrum of meanings rather than dissolving it.

A recent review of functional modeling approaches [1] provides a clear illustration of this ambivalence in engineering towards the different meanings of function. In the introduction of this impressive review of 18 approaches the authors identify functional modeling as a useful means in product designing. It allows engineers to link the small number of initial requirements with the ‘millions of details in the final technical product description[s]’. And functional modeling provides collaborating engineers originating from different disciplines with a ‘common representation framework above the single domains’. Yet, in their conclusions the authors acknowledge that although they intend ‘to build up a general [functional modeling] framework’ by their review, not all approaches are ‘compatible’ with each other. The variety in approaches is suggested to be ‘a result of the different disciplines in which the [functional modeling] engineers are educated’ and ‘the different application domains the particular [approaches] are aimed at.’ Especially this last observation suggests replacing a number of the approaches, since if functional modeling remains to be domain specific, it cannot possibly provide engineers with the envisaged common representation framework that rises above the domains. Some of the reviewed approaches were actually meant to replace other existing approaches, or at least to incorporate them (e.g., the one in [2,3]), yet also these revisionary approaches end up in the review side-by-side to the approaches they aim to replace or incorporate.

A conclusion that can be drawn from this review [1] is that currently the concept of function is used with more than one meaning in engineering, and that these meanings exist side-by-side for a good reason. An analysis of this concept therefore may better not be aimed at determining the single right meaning, but rather attempt to relate the different approaches towards understanding functions, and explain their co-existence. In this paper I take up this alternative analysis. On the basis of a broad and general model of technical devices by Brown and Blessing [4] five key concepts are isolated in terms of which descriptions of devices are given: *function*, of course, and also *structure*, *behavior*, *action*, and *goal*. Then, generalizing a perspective by Vermaas and Houkes [5] on how the concept of function can be employed for both connecting and separating physicochemical descriptions and intentional descriptions of technical devices, I argue with the model for the following position. The concept of function can be given different meanings and the precise meaning it gets depends on the aim for which it is employed. One can employ this concept for connecting the physicochemical descriptions of devices in terms of the key concepts structure and behavior with their intentional descriptions in terms of actions and goals, and one can employ it also for separating these two types of descriptions. Moreover, one can employ the concept of function for simplifying full descriptions of devices to descriptions in which references to some of the five key concepts are by-passed. A number of the engineering approaches towards understanding functions now represent such simplifications. This observation gives the possibility to explain the different meanings of function these approaches advance, and their co-existence: the different meanings are due to the different ways in which the approaches simplify full descriptions of devices, and the approaches co-exist because the simplifications they represent are all valuable to engineering. The result is that function can be employed to refer to the desired behavior of devices, to the desired effects of that behavior, or even to the goals for which devices are used.

My position is illustrated with an analysis of three particular approaches towards understanding functions: the approach in which functions are represented by or taken as operations on flows of materials, energies, and signals [6,7,8], and then specifically the FM approach by Stone and Wood [7]; the MFM approach by Lind [9]; and the FBS design model by Gero [10].

With the analysis of the co-existence of different approaches towards understanding functions, one can comment on a few assumptions that are made in these approaches and which make them mutually incompatible. In the approaches in which functions are represented by or taken as operations on flows of materials, energies, and signals [6,7,8], it is typically assumed that functions always have both input flows and output flows. From a general functional modeling perspective such an assumption seems easily challengeable; there also exist approaches that adopt similar concepts of function and in which functions can have only input or only output flows [9]. But when taking into account that approaches employ the concept of function differently and attach different meanings to it, this assumption can be defended. A similar point holds for the related assumption that these flows should satisfy conservation laws, that is, that for instance the energy input should be equal to the energy output ([8] and probably also [6,7]). This assumption is again absent in [9]. Finally I consider the assumption made in, for instance, [7] that functions can be characterized by both verb-noun pairs and operations-on-flows, where these characterizations are related by the rule that the verbs correspond to the operations and the nouns to the (main) flows [11]. From a general perspective also this assumption can be challenged [12], but this challenge is again undercut when taking into account that approaches employ the concept of function differently.

The model of technical devices is introduced in section 2 and analyzed in section 3 in terms of the five key concepts. The different ways in which functional descriptions can be used in the model are presented in sections 4 and 5. Section 6 is for discussing the assumptions made in specific approaches towards understanding functions, and conclusions are drawn in section 7.

2 THE BROWN-BLESSING MODEL

The model by David Brown and Luciënne Blessing of technical devices [4], section 2, builds on work by Chandrasekaran and Josephson [13]. It is called a model of *function* but may be interpreted more generally as a model of *using* technical devices, since it describes functions relative to the behavior of devices and to the goals and operations of agents with these devices. Brown and Blessing employed this general character of their model to analyze the concept of affordance [14] in terms of functions, goals and operations; in this paper it is used to analyze the concept of function itself.

In the model a technical *device D* is approached from the perspective of an agent who uses the device by means of a *plan P* to realize a *goal G*. This goal is a state in the world desired by the agent. The plan P consists of a set of executable *operations* or actions $\{O_1, O_2, \ldots, O_i, \ldots, O_p\}$, which are ordered sequentially or otherwise. These operations, when executed by the agent in the right ordering, should make progress towards achieving the goal G. An operation O_i can be executed successfully if conditions C_i specific to that operation O_i are met. If an operation O_i involves a device D, this device contributes to providing the conditions C_i. This contribution of the device to the conditions C_i is captured by desired *behavioral constraints B* on the *behavior* of the device D within its environment.

Let E_j be an environment in which a device D can be placed. The interactions that exist between D and this environment E_j define the *mode of deployment $M(D,E_j)$* of the device, a concept which originates from [13]. These interactions lead to an evolution of the states of both the device D and the environment E_j, and this behavior can be described by sets of behavioral constraints $B = \{B_1, B_2, \ldots, B_k, \ldots, B_q\}$ on the state evolutions of D and E_j. A behavioral constraint B_k associated to a mode of deployment $M(D,E_j)$ need not necessarily be satisfied by the behavior of D and E_j, but should be testable in that mode of deployment. If a particular set B of constraints is satisfied, it can be said that the device D plays a *role* in the environment E_j. And if a role of the device D is desired by an agent, the set of behavioral constraints associated to that role provides a *function* of D in the environment E_j.

If an operation O_i of a plan P with goal G involves a device D in an environment E_j, then this operation defines a mode of deployment $M(D,E_j)$ for that device. The conditions C_i required by the operation O_i may be conditions on the behavior of D in E_j, that is, they may have the form of behavioral constraints B on D in E_j. If these behavioral constraints B implied by the conditions C_i are satisfied, then the constraints B provide automatically a function of the device D in E_j. This last conclusion follows because the agent who uses the device D for realizing a goal G, desires that the device plays the role associated to the behavioral constraints B on D in E_j implied by the conditions C_i: this agent desires to carry out the plan P to realize the goal G, thus desires that the conditions C_i for the different operations O_i are satisfied, and thus desires that the behavioral constraints B implied by these conditions C_i are satisfied.

Brown and Blessing introduce writing with a pen to illustrate their model. The agent is then a person who has the goal G to provide another person with some information. The plan P consists of operations $\{O_1, O_2, \ldots, O_i, \ldots, O_p\}$ by the first person with a pen and paper, spelled out as ‘grip the pen’, ‘orient pen’, ‘put pen tip to paper’, ‘apply pressure’, and ‘move pen’. These operations define a mode of deployment M(pen, paper) of the pen described as ‘human is gripping pen’, ‘pen is tip down’, ‘tip is in contact with paper’, and ‘the tip exerts pressure on the paper’. The behavioral constraints B implied by the conditions C_i that should be met for executing these operations successfully are ‘ink flows from the tip’, ‘ink coats the paper’, and ‘the tip is moving’. These constraints B finally define a role for the pen, which is the pen’s function when the constraints are satisfied. Brown and Blessing capture this function in different ways. A *device-centric* description is that ‘the function of the pen is to cause ink to flow out of its ink container onto the tip’. *Environment-centric* descriptions are that the pen’s function is ‘to cause a piece of paper to have ink on it’ or ‘to communicate information’.

This last distinction between device-centric and environment-centric descriptions of functions originates also from [13], and is introduced to accommodate different meanings of the concept of function that are in use. Functional descriptions may be employed to single out desired behavior of devices, or may be used to single out more abstractly the desired effects devices have on their environments. Descriptions of the first type are device-centric descriptions; descriptions of the second are environment-centric ones.

The occurrence of device-centric *and* environment-centric descriptions of functions in the Brown-Blessing model already demonstrates that in engineering the concept of function may be employed in more than one way and that this has an impact on its meaning. After slightly abstracting from the Brown-Blessing model, I argue in section 4 that function can be employed in even more ways.

3 FIVE KEY CONCEPTS

The Brown-Blessing model puts forward four key concepts in engineering descriptions of technical devices. It speaks, first, of *goals* of agents that describe the states in the world that agents desire to realize when using devices. Second, it introduces operations that describe the *actions* that agents execute when using the device (I prefer the term *action* for what Brown and Blessing call operations because action emphasizes that they concerns *intentional* operations by agents: ‘gripping a pen’ is an operation agents intentionally execute, and is in that sense an action, whereas 'transporting warmth to the pen' by gripping it is an operation agents do unintentionally, and thus not an action). Third, *functions* describe the roles the device should play in its environment for the agent when the agent is using the device. Fourth, *behavior* describes the way in which the physicochemical state of the device evolves in its environment, when it is used but also when it is not used.

A fifth key concept in engineering descriptions of technical devices is *structure*. Structural descriptions describe the physicochemical materials and fields of the device and its environment, the spatiotemporal configuration of these materials and fields, and their mutual physicochemical interactions. Structure is less accentuated by Brown and Blessing, yet often introduced in engineering models of devices (e.g., [10,13,15]).

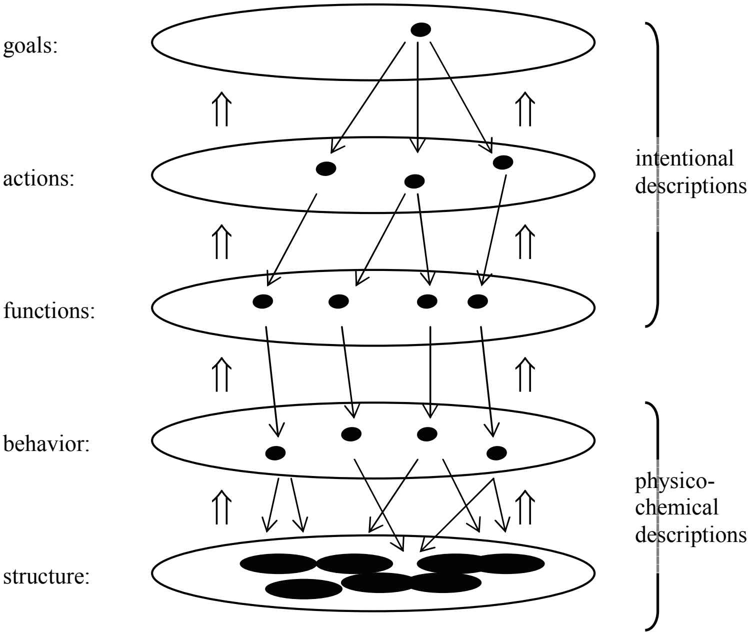

Figure 1. The conceptual layering of models of technical devices

The relations between these five key concepts are also given, and they reveal a sequential, chain-like ordering: goals and actions are pair-wise related; actions, functions, and behavior are related in a triple; and behavior and structure are again pair-wise related. By means of this chain of relations, one can also determine, say, the relations between goals and functions, or between goals, behavior, and structure. Yet the sequential ordering of the key concepts seems fundamental and reveals a layered conceptual structure of models of devices, as depicted in Figure 1. When describing technical devices, one can proceed in two directions through this conceptual layering. Brown and Blessing adopt an *agentive perspective* in which one starts by considering the goals of an agent and then works one's way downwards through the layers by relating goals to actions, actions to functions, and so on. The relations can also be given from a *structural perspective* in which one starts with the structure of the device and then works one's way upwards through the layers.

From the agentive perspective the *goal* for which a device is used is related through a *plan* to the *actions* this use consists of: the plan is of a series of actions, ordered sequentially or otherwise, for which holds that executing them in the given ordering realizes the goal (Brown and Blessing [4] speak about plans *simpliciter*, so does, e.g., [16]; in [17,18] the term is *use plan*). In principle the goal is not uniquely determining the actions; there may be two or more plans consisting of different actions for realizing a goal (the goal of providing other agents with information can be realized by actions with pens and by different actions with, say, computer terminals). An *action* with a device is related to the *functions* and the *behavior* of the device by means of conditions on the device: for executing an action with the device successfully the device should be able to exercise certain behavior, which is called its function [4,17]. An action again does not fix a function and behavior uniquely; there may be different behaviors that make executing the action successful (the action of leaving marks on paper with a pen may be successful if the pen leaves trails of ink on the paper but also if it leaves trails of carbon). The *behavior* and *structure* of a device is finally related through physics, chemistry, and the technical sciences: a device can exercise certain behavior by the evolution of the physicochemical state of the device in its environment, which comes about through the physicochemical interactions of the materials and fields in the device and in its environment, as determined by science and technology. Again specific behavior can be exercised by different structures (consider the different types of ink pens that are available).

A description of a device from the agentive perspective is typically a *subjective*, *normative*, and *partial* description because it focuses on what is required from the device given a specific goal. One starts with that goal, which is a state of the world that is *desired* by the agent. Given this goal a plan with specific actions with the device is singled out, that *should* realize the goal. Given these actions, the device is *required* to be able to exercise specific *desired* behavior, captured by behavioral *constraints*, and called its function. Given the goal, this behavior is its *desired* behavior. And finally this behavior singles out a specific structure that the device and its environment *should* have in order to let the device be usable for realizing the goal.

One can now argue that a description of a device from the structural perspective is *objective* in the sense of that it abstracts from a specific goal in the description and aims at *completeness*. The description of the structure of a device from this second perspective gives in principle a complete description of that structure, and not only of those features that are required by some use. The behavioral description gives in principle all behavior the device can exercise on the basis of its structure. And so on: in the functional description all possible behavior singles out possible functions of the device; in the description of actions, all actions agents can perform with the device are included, and in the description of the goals all goals are included that agents can realize with plans of those actions.

In Figure 1 the agentive perspective is depicted by single arrows '→' and its partial character is captured by the dots in the circles, indicating that in this perspective one considers limited descriptions – the dots – of a device by means of the key concepts, which cover only parts of the full description – the circles. For a specific goal, these arrows single out specific actions, specific behavior as functions, and specific parts of the structure, namely those parts required if the device is to be usable for realizing the goal. The structural perspective is depicted by mappings '⇒', and the completeness of this perspective is captured by the circles. The complete structure of the device, determines all types of behavior of the device, and so on.

By calling a description of a device from an agentive perspective 'subjective' and one from a structural perspective 'objective', I depart from a usual position in engineering methodology to take functional descriptions and descriptions in terms of goals as subjective and to take structural and behavioral descriptions as objective (e.g., [1], section 2). The reason for this departure is that structural and behavioral descriptions can also be subjective. When one adopts an agentive perspective, say, when one is designing a device by which users can realize a given goal, the final structural and behavioral descriptions are subjective in the sense that they specify normatively only those features the device has to have in order to realize that goal. Structural and behavioral features that are irrelevant for that use – in the case of the pen, for instance its electrical charge and its ability to puncture paper – are for good reasons omitted. And the distinction between relevant and irrelevant features has its origin in the subjective goal for which the device is designed. When taking a structural perspective, e.g., when analyzing the ways in which a device can be harmful to, say, small children, one in principle aims at an objective list of such harms that includes all possible intentional uses of the device by children. Hence, descriptions of actions that can be executed with a device, can be objective in the sense of being independent of a particular preferred goal.

Descriptions of devices in terms of functions, actions, and goals can, however, be contrasted with structural and behavioral descriptions of these devices by calling them *intentional descriptions*: in descriptions of devices in terms of functions, actions, and goals, intentional terms like intention, desire, plan, and goal are added to the *physicochemical* terms in which structural and behavioral descriptions are given [5].

A final remark concerns ‘mode of deployment’. I avoided this term when giving the relations between the five key concepts because it is a hybrid term relative to the conceptual layering of descriptions of technical devices. A mode of deployment, as introduced by Chandrasekaran and Josephson ([13], section 5.1.1), may refer to structural relations between a device and the entities in its environment, *and* may refer to actions of agents with the device. In the model of technical devices, structural relations and actions are quite different things, showing the hybridity in the reference of mode of deployment. This remark should however not be taken as a plea against terms that refer to different key concepts or that ‘cut across’ the conceptual layering by directly relating “distant” key concepts like structure and actions. In explaining the flexible meaning of the concept of function in engineering, I exactly use this possibility of cutting across the conceptual layering in descriptions of devices.

4 CONCEPTUAL CLOAKING

Brown and Blessing already introduced two different meanings of the concept of function in their model: function as desired behavior as given in device-centric descriptions, and function as desired effect as given in environment-centric descriptions. Both types of descriptions capture the role a device should play in its environment for the agent when the agent is using the device, and they do so differently: device-centric descriptions capture this role by singling out the particular behavior that the device should exercise when it is used, and environment-centric descriptions capture it by the effects the device should have when it is used. In principle one can now conclude that the term function is ambiguous in the model, and argue that a model in which function has one meaning is to be preferred. Brown and Blessing seem to take the device-centric meaning of function as desired behavior as more fundamental. But they introduce the second environment-centric meaning in their model to accommodate that ‘in natural language one can describe the function of a device without knowing anything about its structure, or even about exactly what behaviors are at the [device] to [environment] interface.’ ([4], section 2.1) Hence, the concept of function has two meanings for a good reason: it is a concept that may be employed to refer to the desired behavior of devices in use, which links functions to the behavior of devices, and it is a concept that may be employed to refer to effects of devices in use, which abstracts functions from the behavior of devices.

This flexibility in the meaning of the concept of function can be explained by two further observations about this concept. The first is that function is a *bridging* concept between ‘human intention and physical behavior of [devices].’ ([1], sections 2.2 and 2.3, with therein references to [13,19,20,21,22]) The second is that this concept can also be employed to *separate* the intentional and physicochemical descriptions of devices, as argued for by Vermaas and Houkes [5]. The bridging nature of the concept of function is accommodated in the relations between the five key concepts. The goals and actions involved in using devices are by these relations connected to the behavior and structure of those devices *via* the functions of the devices. The separating nature of the concept of function is mentioned in the quote of Brown and Blessing by which they motivate the introduction of the environment-centric meaning of function: ‘in natural language one can describe the function of a device without knowing anything about its structure, or even about exactly what behaviors are at the [device] to [environment] interface.’ The environment-centric meaning of the term function is thus suitable if one gives an intentional description of a device, and if one wants to separate it from a physicochemical description to which the device-centric meaning of function is a part.

This separating is useful for engineers because the Brown-Blessing model is relatively broad and rich: full descriptions of devices phrased in terms of all five key concepts are rather elaborated. Hence, under particular circumstances it makes sense to simplify these full descriptions to more convenient complexity by *cloaking* parts of the descriptions. When adopting an agentive perspective and describing a particular use of a device, one can, for instance, focus on the goals and actions and black-box the behavioral and structural descriptions of the device. One then starts with the goal for which a device is to be used, identifies the plan of actions by which this goal is to be realized, and ends the description by giving the functions the device has to have in order to let the actions be successful. Such a description is a purely *intentional description* of the device in which one cloaks its physicochemical description: the functional description by which it ends identifies the behavioral effects the device should realize and in that way highlights the desired behavior but does not determine that behavior and the structure the device is required to have for exercising the behavior. These intentional descriptions are typically the ones users give of devices. And the concept of function is in these descriptions employed in its environment-centric meaning, since environment-centric functions merely fix the behavioral effects of devices; employing functions in their device-centric meaning would introduce unnecessary explicit behavioral descriptions in intentional descriptions of devices. In terms of the example of the pen: the pen is used by an agent for communicating information to another person; the agent realizes this goal by ‘gripping the pen’, ‘orienting pen’, and so on; and for this the pen has to have the (environment-centric) function ‘to cause a piece of paper to have ink on it’. What structure and behavior the pen has to have for displaying these effects can be ignored by users.

An intentional description of the use of the device can clearly be extended to a full-blown description by adding to it the missing behavioral and structural parts. This extension starts with the functions of the device, then identifies the behavior the device should be able to exercise to have these functions, and ends with giving the structure the device has to have in order to display this behavior. This extension is again a *cloaked* description of the device and a description that is more or less purely *physicochemical*; now one focuses on the behavior and the structure of the device and black-boxes the intentional description of it; the functional description by which it starts highlights the desired behavior the device should exercise, yet it cloaks the actions agents execute with it and the goals for which they do so. For such physicochemical descriptions of devices the concept of function can be both employed in its environment-centric and its device-centric meanings. If it is employed in its environment-centric meaning, the description should include a relation between the function – the desired behavioral effect – and the desired behavior the device has to exercise; if function is employed in the device-centric meaning, a functional description is a description of the device’s desired behavior immediately. These physicochemical descriptions are ones engineers may give when they are designing devices. In terms of the pen: designing starts by the task of having a device with the function ‘to cause a piece of paper to have ink on it’, the designer determines the behavior this device has to have in order to display this effect, and finally gives the structure of a pen, such that it can be made and handed over to its prospective users.

The possibility to give descriptions of technical devices in which parts of the full description are cloaked, is valuable, and my position that engineers employ this possibility is thus not critical; cloaking introduces ambiguity in the meaning of the concept of function, but it is worth the price. When giving users information about how a device is to be used, it may be efficient to indeed cloak the physicochemical part of the full description. And in designing it may be useful to cloak the intentional part. When designing components of devices – the ink in the pen – or when designing devices with fixed goals and user actions – the pens themselves – it is efficient to cloak the intentional part of the full description, or at least bits of that part. There are, moreover, other engineering ways in which full descriptions of technical devices in terms of all five key concepts can be simplified, and these simplifications again have an effect on the meaning in which the concept of function is employed.

5 CONCEPTUAL BY-PASSING

In intentional and physicochemical descriptions full descriptions of technical devices are simplified for users and for engineers in specific cases of designing. In other cases engineers may need more complex descriptions, but when surveying the literature, it is fair to say that full descriptions in terms of all five key concepts are typically not adopted. Engineering descriptions may specifically not include the actions of agents with devices and, as we will see, also suppress the key concept of behavior. In terms of the conceptual layering, depicted in Figure 1, such engineering descriptions skip one or more of the layers, which may be captured with the term of conceptually *by-passing*. A number of the different engineering approaches towards understanding functions can now be understood as providing such by-passing simplifications. These approaches each attach a particular meaning to the concept of function and advance related models for describing technical devices in, say, designing.

My first example is the approach in which functions are taken or represented as operations on flows of materials, energies, and signals, and in which it is assumed that these operations always have input and output flows [6,7,8]. Pahl and Beitz advanced this approach [6] but I focus here on the FM (*Functional Modeling*) model of designing by Stone and Wood [7]. By this FM model designing starts with a description of the overall product function of the product to be designed, which is derived from customer needs. This product function is captured by a (linguistic) verb-object expression and represented as a black-boxed operation on flows of materials, energies, and signals. This overall product function is then decomposed into a network of basic functions as defined by libraries of basic operations and basic flows [23] (Stone and Wood also call the basic operations functions, I ignore this meaning of function in this paper [24]). And by means of this network of basic functions design solutions are searched and composed.

Considered relative to full five-key-concepts-descriptions of devices, designing engineers reason in FM in one step from goals to functions and then in one step from functions to structure, by-passing thus the actions users execute with the device and the behavior devices exercise (design reasoning is of course cycling between customer needs and design solutions, but for analyzing the concept of function this iterative character is less important). Functions are in FM employed to directly relate goals with structure, and have the (device-centric) meaning of desired behavior of the device. Because of the assumption that functions are or are represented as operations that always have both input and output flows, functions cannot refer to only the effects of the desired behavior. When function would be employed in the desired effect meaning, the function of a sound barrier could be the operation of just *absorbing* a flow of acoustic energy, i.e., without an output flow. Yet that option is ruled out in FM; such a function has to be represented as the *conversion* of the flow of acoustic energy to, say, thermal energy, thus highlighting the desired behavior the device has to exercise. Stone and Wood do not explicitly define their concept of function as desired behavior since they typically do not mention the concept of behavior (more recent work does mention behavior [25]). Pahl and Beitz define functions as an intended relationship between inputs and outputs also without referring to behaviors. Yet one can defend that Pahl and Beitz at least implicitly refer to behavior when they add that the subfunctions – the functions in which overall functions are decomposed – are usually fulfilled by physical, chemical, and biological processes ([6], sections 2.1.3 and 2.1.4).

The second example is the MFM (*Multilevel Flow Modeling*) approach by Lind in which functions of in particular industrial plants are understood as representing 'the roles the designer intended a system should have in the achievement of the goals of the systems(s) of which it is a part' [9]. In this approach functions are represented by sets of mass, energy, activity, and information flows, and a distinction is made between functions of the plant itself, represented by mass and energy flows, and functions of operators or control systems of the plant, represented by activity and information flows. Now, however, no assumption is made that the plant functions always have input *and* output flows; 'source functions' actually have an output flow of matter or energy only. The key concepts in an MFM model of a plant are goal, function, behavior, and structure. By including functions of operators, the actions of those operators are considered in the MFM approach. But those are actions of the operators and should not be confused with the actions of the agents who are using the plant. The relevant example discussed in [9] is a power plant boiler. This plant has the main goal of generating electricity, meaning that the agents who use the plant are those who use the generated electricity. Actions of such using agents are ignored in MFM models. An MFM model contains the goals for the plant, which consists of its main goal and the goals of the structural parts of the plant. The main goal and the goals of the parts are related by a 'goal decomposition'. The goals of the structural parts are achieved by the functions of these parts, which may be functions of the parts, or functions of operators/controller systems. These functions are related by a 'functional decomposition'. In [9] behavioral descriptions are announced as being also elements of MFM models, but they are not actually given.

Considered relative to full five-key-concepts-descriptions of devices, MFM models by-pass the key concept of action (by users). Behavioral descriptions are, as said, not yet included in the model but conceptually behavior is not by-passed. In the discussion of an example it is for instance said that the functions 'describe how the behaviours of [..] components are useful for the achievement of various purposes or goals'. Functions are in MFM thus employed to relate goals of industrial plants with their behavior, and can have now the (environment-centric) meaning of desired effect of the behavior of devices; because functions can have only input flows or only output flows of matter or energy, they do not describe the behavior of the device having that effect. (Here I assume that behavior is to be modeled by operations on flows, where output flows of in particular matter and energy, should be matched by input flows of matter and energy; see also the next section.)

A final example is the FBS (*Function-Behavior-Structure*) design model of Gero [10,26]. In this model designing is in its barest form an activity in which functions are transformed into design descriptions of devices that can perform these functions. These functions originate from clients, and the design descriptions determine how the devices can be made. The functions are transformed into design descriptions via elementary design steps in which also the behavior of the devices and their structure are considered. It may seem that in the FBS model designers fully ignore the goals and actions related to the use of devices. Yet, Gero defines functions as the 'design intentions or purposes' related to devices [27]. If these design intentions or purposes are the goals users have with the device, the distinction between the concepts of goal and function has disappeared. The reasoning then proceeds from functions-as-goals straight to behavior, and then to structure, leading to descriptions in which the actions of users with devices are by-passed. If, however, design intentions or purposes refer to the effects the device should have in use, functions are used in the (environment-centric) meaning of desired effects. In this second case goals of users and their actions are cloaked in the reasoning of designers, and the reasoning leads to physicochemical descriptions, linking functions to behavior and structure. Gero's writing on the FBS model offers evidence that functions can have both meanings: the function of a window is, for instance, described as 'providing view', which refers more to intentional goals of using agents, and 'controlling noise', which refers more to the effects of behavior of the window ([26], section 4; see also [28]).

These three examples show that the full five-key-concepts-descriptions of technical devices can be simplified in more than one way by by-passing key concepts in these descriptions. These simplifications again have an effect on the precise meaning by which the concept of function is employed: this meaning alternates between the device-centric meaning of desired behavior, the environment-centric meaning of desired effect of a device, and functions may even refer to the goals for which devices are used. Hence, one can explain the fact that there exist in engineering different approaches towards understanding functions by noting that these approaches represent different simplifications of the full five-key-concepts-descriptions of devices, simplifications that all may be useful in engineering. It is, moreover, now reasonable that these different approaches exist side-by-side and that there is no felt need for defending one and disproving others: the simplifications these approaches represent may all be considered as co-existing useful conceptual tools, which engineers may choose to employ though not choose to employ simultaneously. Each approach has the advantage that the full five-key-concepts-descriptions of devices are reduced to more manageable size by cloaking or by-passing those parts of the full description that are deemed irrelevant. And from this perspective it seems not to make sense to criticize specific approaches. The observation, for instance, that the modelling of functions in terms of operations on flows does not describe in detail the intentions related to devices (see [1], section 2.1), seems not a critical observation: when engineers are not interested in these details, approaches that advance this modelling seem fit to the job. Yet the disadvantage is that the meaning of the concept of function depends on the approach one chooses for simplifying the full descriptions of technical devices: the concept of function ends up with a flexible meaning in engineering.

6 INCOMPATIBLE ASSUMPTIONS

One of the conclusions of the review [1] of the different available approaches towards modeling functions is that they are not all compatible. With this paper's analysis, this incompatibility can be understood in part as due to the different simplifications the approaches represent. They all advance different simplifications of the full five-key-concepts-descriptions of devices, and employ the concept of function with different meanings suitable to the simplifications. In this final section the incompatibility of the approaches towards understanding functions is considered in more detail by commenting on assumptions made about functions in these approaches. In the previous section some of these assumptions were already introduced for identifying the meanings approaches attach to the concept of function. In this section I reverse the argumentative order and show that these assumptions make sense given the meanings these approaches attach to the concept of function. This reversal introduces some circularity: the assumptions were used for identifying the meaning approaches attach to functions; hence it is obvious that given these identified meanings the assumptions make sense. This circularity certainly holds for the first case I consider.

In approaches [6,7,8] like FM in which functions are represented by or taken as operations on flows of materials, energies, and signals, it is typically assumed that functions always have both input and output flows. Such an assumption seems unnecessary in general. Functions can also be represented by flows without this constraint, as is illustrated by the MFM modeling [9] in which source functions are conveniently represented by output flows only. Similar sink functions are represented in MFM as functions with only input flows; the function of the mentioned sound barrier may be just to absorb an input acoustic energy flow. If one now takes into account the meaning that is attached to the concept of function in the different approaches, the assumption again is defendable. In approaches like FM, functions of devices refer to the behavior of those devices that are desired. And when considering the behavior of devices, it makes from a physicochemical point of view sense that flows of materials and energies do not disappear. A flow of matter or energy entering the device should be matched by a flow leaving it or staying within it, and a flow of matter or energy leaving the device should originate from an input flow from outside or from within the device. From a physicochemical perspective the behavior of a sound barrier of absorbing acoustic energy is indeed a process of converting this energy to thermal energy, and the electrical energy that a battery produces should be matched by a decrease of the chemical energy in the battery. Yet, it is equally defendable that in MFM this assumption that functions always have both input flows and output flows is dropped. In MFM functions refer to desired effects of behavior and the desired effects of a sound barrier and a battery are simply to absorb acoustic energy and to produce electrical energy.

A similar point holds for the related assumption that the flows representing functions should satisfy the conservation laws of physics for matter and energy. In [8] this additional assumption is explicitly introduced and in other approaches [6,7] in which functions are represented by or taken as operations on flows of materials, energies, and signals, it is also in play. Now, since in all these approaches functions refer to desired behavior, and behavior of devices is subject to conservation laws, this second assumption again makes perfect sense. Yet, in approaches in which functions do not refer to desired behavior, like MFM, the flows representing functions need not satisfy this assumption. When functions refer to desired behavioral effects, descriptions of functions may violate, say the conservation law of energy, as is illustrated by the sound barrier and the battery. In this case the battery just has the function of producing electrical energy (but a description of the behavior of the battery in MFM is clearly satisfying conservation laws).

Finally I consider the assumption made in, for instance, FM [7] that functions can be characterized by both verb-noun pairs and operations-on-flows, where these characterizations are related by the rule that the verbs correspond to the operations and the nouns to the (main) flows [11]. This assumption is, for instance, used in the FM methodology when overall product functions of the product to be designed are derived from customer needs: those customer needs can be phrased in terms of the more discursive verb-noun pairs, say, as ‘popping corn’, and then by the rule be transposed into more descriptive operations-on-flows descriptions, say, as the conversion of an input flow of corn kernels to an output flow of popcorn. Yet the generality of the rule can be challenged by considering functions that can be phrased in terms of verb-noun pairs but that are not by the rule transposed into sensible operations-on-flows descriptions of those functions. The examples are now the ‘detecting planes’ function of radar and the ‘cool human body’ function of an electrical fan [12,29]: application of the rule to these verb-noun pairs lead to representations of the functions of radar and electrical fans by which flows of planes and human bodies go through these devices. But this challenge is again undercut when acknowledging that in the FM approach functions refer to desired behavior of devices. If application of the rule is limited to only verb-noun pairs that characterize behavior of devices, the challenge disappears: ‘detecting planes’ and ‘cool human body’ can then be identified as characterizations of the goals or desired effects of radar and electrical fans, and rejected as characterizations of desired behavior of those devices.

7 CONCLUSIONS

In this paper I have analyzed the concept of function as it is used in engineering. The analysis started with the observation that there co-exist different approaches towards understanding functions. These approaches attach different meanings to the concept of function, and the analysis was aimed at explaining the co-existence of the approaches rather than at arguing for adopting one preferred meaning.

On the basis of a broad and general model of technical devices by Brown and Blessing [4] five key concepts in descriptions of technical devices were isolated: *structure*, *behavior*, *function*, *action*, and *goal*. A full description of a technical device makes use of all five concepts, linking the goal for which a device is used by an agent to the actions this agent has to execute with the device, linking those actions with the functions and behavior of the device, and linking the behavior of the device to its structure. Then, a number of ways were introduced by which these full descriptions can be cut down to manageable sizes. One can cloak the part of the description that refers to actions and goals, arriving at a physicochemical description of the device in which merely the functions of a device are related to its behavior and structure. One can cloak the part of a full description that refers to structure and behavior, arriving at an intentional description of a device in which merely the functions of the device are related to the actions and goals of users. And one can by-pass the concepts of behavior, action, or both, arriving at a simplified description that still links goals of users to the structure of devices. These different ways of cutting down full descriptions of devices have, however, an effect on the precise meaning in which the concept of function is employed. In physicochemical descriptions functions may refer to desired behavior of the device or to the desired effects of this behavior. In intentional descriptions functions refer to the desired effects of the behavior of devices. And in the descriptions in which key concepts are by-passed, functions may refer to the goals for which agents use devices. The concept of function thus has a flexible meaning in engineering, a meaning that depends on the particular way in which one cuts down the full description of technical devices.

Engineering approaches towards understanding functions were taken as representing different ways of simplifying full descriptions of technical devices. In Stone and Woods' FM approach [7] the concepts of behavior and action are by-passed in descriptions of devices, and the concept of function is employed in its meaning of desired behavior. In Lind's MFM approach [9] the concept of action is by-passed, and the concept of function is employed in its meaning of desired effect. In Gero's FBS approach [10] the concept of action is by-passed and the concept of goal sometimes cloaked. In that approach the concept of function is employed in its meanings of desired effect or of goal.

The upshot of this argument is that the different approaches towards understanding functions co-exist because the different ways in which they simplify full descriptions of devices are all valuable to engineering. There is thus no need for defending one approach and disproving others; the assumptions that are made in the different approaches, which may be challenged from a general point of view, make sense when one takes into account the particular way in which the concept of function is used in approaches. And as long as the different simplifications of the full descriptions of technical devices represented by the different approaches towards understanding functions remain to be valuable to engineering, the concept of function will keep having its flexible meaning.

REFERENCES

[1] Erden M.S., Komoto H., van Beek T.J., D'Amelio V., Echavarria E., and Tomiyama T. A review of function modeling: approaches and applications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2008, 22, 147-169.

[2] Kitamura Y. and Mizoguchi R. Ontology-based systematization of functional knowledge. *Journal of Engineering Design*, 2004, 15(4), 327-351.

[3] Kitamura Y., Kashiwase M., Fuse M., and Mizoguchi R. Deployment of ontological framework of functional design knowledge. *Advanced Engineering Informatics*, 2004, 18(2), 115-127.

[4] Brown D.C. and Blessing L. The relationship between function and affordance. In *ASME 2005 IDETC/CIE Conference*, September 24-28, 2005, Long Beach, California, USA, paper no. DECT2005-85017.

[5] Vermaas P.E. and Houkes W. Technical functions: a drawbridge between the intentional and structural natures of technical artefacts. *Studies in the History and Philosophy of Science*, 2006, 37, 5-18.

[6] Pahl G., Beitz W., Feldhusen J., and Grote K.H. *Engineering Design: A Systematic Approach*, 3rd edition, 2007 (Springer, London).

[7] Stone R.B. and Wood K.L. Development of a Functional Basis for design. *Journal of Mechanical Design*, 2000, 122, 359-370.

[8] Modarres M. and Cheon S.W. Function-centered modeling of engineering systems using the goal tree–success tree technique and functional primitives. *Reliability Engineering and System Safety*, 1999, 64, 181-200.

[9] Lind M. Modeling goals and functions of complex plants. *Applied Artificial Intelligence*, 1994, 8, 259-283.

[10] Gero J.S. Design prototypes: a knowledge representation schema for design. *AI Magazine*, 1990, 11(4), 26-36.

[11] Jakobsen K., Sigurjónsson J., and Jakobsen Ø. Formalized specification of functional requirements. *Design Studies*, 1991, 12, 221-224.

[12] Vermaas P.E. On engineering meanings and representations of technical functions. In *ASME 2008 IDETC/CIE Conference*, August 3-6, 2008, New York City, New York, USA, paper no DETC2008-49342.

[13] Chandrasekaran B. and Josephson J.R. Function in device representation. *Engineering with*

Computers, 2000, 16, 162-177.

[14] Maier J.R.A. and Fadel G.M. Affordance-based methods for design. In *ASME 2003 IDETC/CIE Conference*, September 2-6, 2003, Chicago, Illinois, USA, paper no. DECT2003/DTM-48673.

[15] Rosenman M.A. and Gero J.S. Purpose and function in design: from the socio-cultural to the techno-physical. *Design Studies*, 1998, 19, 161-186.

[16] Roozenburg N.F.M. and Eekels J. *Product Design: Fundamentals and Methods,* 1995 (John Wiley & Sons, Chichester).

[17] Houkes W., Vermaas P.E., Dorst K., and De Vries M.J. Design and use as plans: an action-theoretical account. *Design Studies*, 2002, 23, 303-320.

[18] Vermaas P.E. and Houkes W. Developing plans of use: an alternative analysis of engineering designing. In *International Conference on Engineering Design, ICED'03*, Stockholm, August 19-21, 2003.

[19] Balachandran M. and Gero J.S. Role of prototypes in integrated expert systems and CAD systems. In *Applications of Artificial Intelligence in Engineering V*, Vol. 1, 1990, pp. 195-211 (Springer, Berlin).

[20] Keuneke A. Device representation: the significance of functional knowledge. *IEEE Expert*, 1991, 6(2), 22-25.

[21] Umeda Y. and Tomiyama T. FBS modeling: modeling scheme of function for conceptual design. In *ProceedingsWorking Papers of the 9th International Workshop on Qualitative Reasoning about Physical Systems*, 1995, pp. 271-278 (Amsterdam).

[22] Deng Y.M., Britton G.A., and Tor S.B. Constraint-based functional design verification for conceptual design. *Computer-Aided Design*, 2000, 32, 889-899.

[23] Hirtz J., Stone R.B., McAdams D.A., Szykman S., and Wood K.L. A Functional Basis for engineering design: reconciling and evolving previous efforts. *Research in Engineering Design*, 2002, 13, 65-82.

[24] Vermaas P.E. The Functional Modelling account of Stone and Wood: some critical remarks. In *International Conference on Engineering Design, ICED'07*, Paris, August 28-30, 2007.

[25] Hutcheson, R.S., McAdams D.A., Stone R.B., Tumer, I.Y. Function-based systems engineering (FUSE) In *International Conference on Engineering Design, ICED'07*, Paris, August 28-30, 2007.

[26] Gero J.S. and Kannengiesser U. The situated function-behaviour-structure framework. *Design Studies*, 2004, 25, 373-391.

[27] Gero J.S., Tham K.W., and Lee H.S. Behaviour: a link between function and structure in design. In *Intelligent computer aided design*, 1992, pp. 193-225 (Elsevier, Amsterdam).

[28] Vermaas P.E. and Dorst K. On the conceptual framework of John Gero's FBS-model and the prescriptive aims of design methodology. *Design Studies*, 2007, 28, 133-157.

[29] Kitamura Y., Takafuji S., and Mizoguchi R. Towards a reference ontology for functional knowledge interoperability. In *ASME 2007 IDETC/CIE Conference*, September 4-7, 2007, Las Vegas, Nevada, USA, paper no. DETC2007-35373.

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