FUNCTIONAL DECOMPOSITION AND MEREOLOGY IN ENGINEERING

Pieter Vermaas and Pawel Garbacz

1 INTRODUCTION

A key characteristic of the engineering sciences is that their descriptions of physical objects and processes are cast not only in structural terms but in functional terms as well. The engineering sciences share this characteristic with biology and with some of the humanities. If, however, it is added that these functional descriptions express the aims for which objects and processes can be employed, the characteristic becomes more discriminative to the engineering sciences.

Functional descriptions in the engineering sciences have been analysed in philosophy. The focus of these analyses has largely been on determining what is meant when an individual technical object or process is ascribed a function.[1] Functional descriptions in the engineering sciences are, however, much richer than individual ascriptions of functions. Design methodologists, for instance, often characterise the initial conceptual phase of engineering designing as one in which engineers reason from a required overall function of some product-to-be to a number of subfunctions that can make up this overall function.[2] In reverse engineering and other explanatory tasks the reasoning may be the other way round, deriving an overall function from a series of subfunctions. And in engineering knowledge bases, functional descriptions of technical objects, processes and their parts are related to one another.[3] This functional reasoning in the engineering sciences leads to descriptions of technical systems in which different functions are related to one another. Functional reasoning leads in particular to *functional decompositions*, which are descriptions in which one overall function is related to a series of subfunctions that, together, make up the overall function. And functional reasoning can be taken to define what can be called a *functional part-whole relationship* by identifying the subfunctions in a functional decomposition as parts of the overall function that they make up. These interrelated functional descriptions have

[1]See Beth Preston's chapter "Philosophical Theories of Artifact Function" in this Handbook.

[2]E.g., [Pahl and Beitz, 1996, Section 2.1; Umeda and Tomiyama, 1997; Chittaro and Kumar, 1998; Stone and Wood, 2000; Chakrabarti and Bligh, 2001; Kitamura *et al.*, 2005/2006; Bell *et al.*, 2007]. See also Peter Kroes' chapter "Foundational Issues of Engineering Design" in this Handbook.

[3]See William H. Wood's chapter "Computational Representations of Function in Engineering Design" in this Handbook, in which reverse engineering also plays a role.

Handbook of the Philosophy of Science. Volume 9: Philosophy of Technology and Engineering Sciences.
Volume editor: Anthonie Meijers. General editors: Dov M. Gabbay, Paul Thagard and John Woods.

received little to no philosophical attention, which probably becomes more clear when it is noted that they are about *functions* only. In functional decompositions overall functions are related to subfunctions and not to, say, the structural parts (the components) of the technical systems that have the overall functions. The functional part-whole relationship described above is similarly a part-whole relationship directly between functions and not a functionally-defined *structural* part-whole relationship between technical systems and their structural parts. *A wall*, for instance, may be a functionally-defined *structural* part of *a house* but the wall is not a subfunction part of the function of the house; rather the function *to support* is a *functional* part of the function *to provide shelter*. In this chapter we consider interrelated functional descriptions of technical systems, specifically functional decompositions and the functional part-whole relationship that such decompositions define.[4] Yet, given the embryonic stage of research, we cannot do more than announcing them as a topic for philosophical analysis; in this chapter we give a first explorative analysis and an incomprehensive sketch of what this analysis may have in store.

1.1 Functional descriptions in engineering

To pin down functional descriptions, functional decompositions and the functional part-whole relationship to which they lead, we introduce some initial notation, anticipating a more thorough exposition in Section 2. Let Φ be the function that is decomposed and let $\phi_1, \phi_2, \ldots, \phi_n$ be the subfunctions into which Φ is decomposed. We write this down as $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$, where $Org(\phi_1, \phi_2, \ldots, \phi_n)$ refers to a functional organisation, that is, a set of functional orderings of the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$. This organisation is introduced, and in Section 2 we do this more systematically, in order to capture that the ordering of subfunctions matters in functional decompositions. If, for instance, the functions ϕ_1 *to heat with 150 degrees centigrade* and ϕ_2 *to cool with 150 degrees centigrade* are temporally ordered, one has two possibilities, which lead to different overall functions: in the area of food processing, the ordering "ϕ_1 and then ϕ_2" may make up the function *to bake*; and the ordering "ϕ_2 and then ϕ_1" may make up the function *to refrigerate*. Hence, an initial reading of $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ is that the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ ordered by the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ provide a decomposition of the function Φ. In general there exist in engineering more than one decompositions of a given function Φ, hence a reading of $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ in which the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ ordered by $Org(\phi_1, \phi_2, \ldots, \phi_n)$ are presented as the unique decomposition of Φ, is to be avoided. A decomposition $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ is a description in which the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ are related to one another by the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$, and are in that organisation making up the function Φ. Moreover, the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ can be taken as the functional parts of the overall function Φ.

[4]See [Simons and Dement, 1996] for an analysis of the structural part-whole relations between technical systems.

With this notation $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$, functional decomposition is analysed in primarily functional terms. The analysis is made broader by also including the objects and processes that are described in functional descriptions. Let S be a technical system that is described functionally by Φ, and let $s_1, s_2, \ldots, s_n$ be the systems that are described by $\phi_1, \phi_2, \ldots, \phi_n$, respectively (the systems $s_1, s_2, \ldots, s_n$ are functionally-defined structural parts of S; in Section 2.1 we discuss the relation between the systems $s_1, s_2, \ldots, s_n$ and S in detail). With references to these systems we can, for instance, characterise more precisely the engineering activities in which functional descriptions play a role.

Conceptual designing, for instance, can be analysed as follows. The starting point of conceptual designing is an overall function Φ and the aim is to determine the physical description of a system S, that is, the product-to-be, that can perform this function Φ. Assuming that this aim cannot be realised immediately by the engineers, i.e., assuming that they cannot derive the physical description of S directly from the description of the overall function, engineers reason by the following intermediate steps. First, they determine a series of subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ and an organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ that defines a decomposition $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ of the overall function. Second, engineers determine objects and processes $s_1, s_2, \ldots, s_n$ that can perform these subfunctions $\phi_1, \phi_2, \ldots, \phi_n$, respectively. And, finally, they arrive at a physical description of S from the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ of the subfunctions[5] and the physical descriptions of $s_1, s_2, \ldots, s_n$.[6] If the description of the overall function Φ is very detailed, one may assume that the entity S consists of only the entities $s_1, s_2, \ldots, s_n$, but if this description is a coarse-grained one, say when Φ is only the primary function of the product-to-be, then S may also contain other entities. Think, for instance, of an aeroplane. If Φ is merely the primary function *to fly*, then the subfunctions in a functional decomposition $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ of this overall function do not single out the systems that enable emergency evacuations of the passengers and crew. But if Φ refers to the more detailed function of *to fly safely*, then a functional decomposition should identify more of these latter systems.

In reverse engineering the overall function Φ and the physical description of the system S are initially known, and the aim is to derive the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$, their organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ and the systems $s_1, s_2, \ldots, s_n$ that perform these subfunctions.[7]

---

[5]De Ridder [2007, Chapter 4] has argued that functional decompositions help engineers in reasoning from a purely functional description Φ of a product-to-be S to its physical description since especially the organisation of the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ gives engineers early in the design process information about the spatiotemporal structure of the product: even if the systems $s_1, s_2, \ldots, s_n$ are still only functionally characterised by $\phi_1, \phi_2, \ldots, \phi_n$, the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ fixes how these systems $s_1, s_2, \ldots, s_n$ are spatiotemporally related.

[6]Conceptual designing is not a process in which these three steps are taken one after the other; in engineering design literature it is emphasised that designing is an iterative process.

[7]In reverse engineering some of the systems $s_1, s_2, \ldots, s_n$ may also be known initially. The objects in the set $\{s_1, s_2, \ldots, s_n\}$ are technical components of S, and it seems reasonable to assume that engineers are able to recognise some of those components. The processes in $\{s_1, s_2, \ldots, s_n\}$ may, however, be more difficult to identify.

In engineering knowledge bases, functional descriptions of technical systems contain all functions $\Phi, \phi_1, \phi_2, \ldots, \phi_n$ related to one another through organisations $Org(\phi_1, \phi_2, \ldots, \phi_n)$ and decompositions $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$.[8] These functional description may also contain the systems $S, s_1, s_2, \ldots, s_n$, and, conversely and more typically, descriptions in engineering knowledge bases are descriptions of the systems $S, s_1, s_2, \ldots, s_n$ to which the functions $\Phi, \phi_1, \phi_2, \ldots, \phi_n$ are added.

With these characterisations of engineering activities, one can also to some extent formulate criteria that functional descriptions and functional reasoning should meet in order to be useful. In conceptual designing the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ should be ones for which, given the technological state of the art, one has available or can find easily the systems $s_1, s_2, \ldots, s_n$ that can perform them (see also Section 5). Decomposing, for instance, a function *to emit light* into the subfunctions *to collect acoustic energy* and *to convert acoustic energy in light* does not help in finding via the entities s_1 and s_2 a physical description of a light source S: currently systems s_2 that can perform the function *to convert acoustic energy in light* are technologically not available. In reverse engineering, assuming that the description of the overall function Φ is sufficiently detailed, the systems $s_1, s_2, \ldots, s_n$ should make up together a substantial part of S, in order to avoid the conclusion that the original designers of S added all kinds of spurious systems to their design of S. Finally, one of the goals for developing knowledge bases is to enhance communication about functional descriptions among engineers of different disciplinary backgrounds, between engineers and computer tools like CAD/CAM systems, and among computer systems. For achieving this goal, at least the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ can be chosen from a standardised set (cf. [Hirtz *et al.*, 2002]; see also Section 5).

1.2 Relevance

The analysis of functional descriptions will be of relevance to a number of existing topics in philosophy, thus providing new and renewed links between the philosophy of the engineering sciences and other more classical domains in philosophy. We see four of such domains: philosophy of technology and philosophy of biology, both specifically with respect to accounts of functions, and epistemology and mereology.

Existing philosophical accounts of the concept of technical functions provide input to the analysis of functional descriptions, and this analysis can in turn be seen as a next step in developing these accounts. The analysis of functional descriptions may in this way yield criteria for judging the accounts, for it is not yet clear if all these accounts can provide for a basis sufficient for taking this next step (we come back to this point in Section 3).

[8] Alternatively one can analyse functional descriptions in engineering knowledge bases as descriptions containing functions $\Phi, \phi_1, \phi_2, \ldots, \phi_n$ related to one another through organisations $\mathrm{Org}(\phi_1, \phi_2, \ldots, \phi_n)$ and a *composition* function (in the mathematical sense) $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$ expressing that the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ ordered by $Org(\phi_1, \phi_2, \ldots, \phi_n)$ make up Φ. We introduce this composition relation in Section 2.

Since the analysis of technical functions is typically related and contrasted to the analysis of biological functions, it is to be expected that the analysis of functional descriptions establishes a similar interaction with philosophy of biology.[9] In that domain there already is attention for the biological counterpart of functional decompositions (e.g., [Wimsatt, 2002]), which is especially manifested in the philosophy of science and epistemology literature on mechanistic explanations. In that literature scientific discoveries in biology and other sciences are interpreted as discoveries and explanation of mechanisms [Machamer *et al.*, 2000; Craver, 2001; Bechtel and Abrahamsen, 2005], where the concept of mechanisms is sometimes explicitly introduced by means of technical artefacts [Craver and Bechtel, 2006]. In such explanations activities of mechanisms are analysed in terms of the organised[10] objects and activities that make up mechanisms. Mechanistic explanations and functional descriptions in engineering are clearly related (Bechtel and Abrahamsen [2005, pp. 432—433] even speak about functional decompositions in the context of mechanistic explanations). A mechanism can arguably be interpreted in engineering as the entity S, the mechanism's activity as the overall functions Φ, and the entities and activities that make up the mechanism as the objects and processes $s_1, s_2, \ldots, s_n$, revealing the epistemic dimension of functional decompositions as explanations. Functional reasoning in engineering is thus a form of explanatory reasoning, albeit one that provides more types of explanations than the one referred to in mechanistic explanations. In conceptual designing a functional decomposition of the overall function Φ of the product-to-be S implies also an explanation of the function Φ in terms of the organised subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ of the systems $s_1, s_2, \ldots, s_n$ (see [de Ridder, 2006]). In reverse engineering and in knowledge bases, functional descriptions may, however, represent reasoning in which the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ and their organisation are, in reverse order, explained in terms of overall functions Φ. We will not further develop these links between engineering functional descriptions, functional descriptions in biology and functional reasoning in epistemology,[11] apart from a few isolated remarks in our concluding Section 6.

Functional decompositions define in two ways part-whole relationships and their analysis may contribute to logic and specifically mereology. First, functional decompositions define a part-whole relation between the systems S and $s_1, s_2, \ldots, s_n$, with S taking the role of whole and $s_1, s_2, \ldots, s_n$ taking the role of parts. These parts are called *functional components* by Peter Simons and Charles Dement [1996, p. 264] and we called them functionally-defined *structural* parts. Simons and Dement have argued that this part-whole relationship is different to a number of other part-whole relationships that are in use in engineering, and that it is not

[9] Through this interaction with biological theories of functions, it may be expected that the analysis of functional decompositions in engineering will eventually also interact with philosophy of mind and the philosophy of the cognitive sciences, since accounts of biological functions are applied in these two domains.

[10] Our notion of the organisation of functions $Org(\phi_1, \phi_2, \ldots, \phi_n)$ is adapted from the notion of organisation as used in the literature on mechanistic explanations.

[11] See [Houkes, 2006] for a broader discussion of functional reasoning in engineering.

coinciding with the standard notion of the part-whole relationship as defined in mereology. Second, functional decompositions define a part-whole relation directly on the level of functions, that is, between the functions Φ and $\phi_1, \phi_2, \ldots, \phi_n$, with Φ taking the role of whole and $\phi_1, \phi_2, \ldots, \phi_n$ taking the role of parts. We called this the *functional* part-whole relationship and this second relationship is to our knowledge not yet considered in mereology even though it may be taken as inducing the first structural part-whole relationship between the systems S and $s_1, s_2, \ldots, s_n$, since these systems are singled out by the functions Φ and $\phi_1, \phi_2, \ldots, \phi_n$ (we come back to the functional part-whole relationship in Section 4).

In addition to being relevant to philosophy, the analysis of functional descriptions can also be of benefit to engineering. Clearly engineering is initially primarily a source to this analysis. But when it will advance, philosophical analysis may contribute to the different engineering uses of functional descriptions. Conceptual clarity provided by the different accounts of technical functions may be of benefit to engineering as a whole; research on the epistemology of functional decompositions will be more of use to design methodology and to functional reasoning, whereas research on mereology may prove to be of value for developing engineering ontologies for knowledge bases (we come back to these points in Section 5).

1.3 Our plan

In the next section we develop our characterisation of functional descriptions by defining the organisation $\mathit{Org}(\phi_1, \phi_2, \ldots, \phi_n)$ of sets of functions and the composition $\mathit{Comp}(\mathit{Org}(\phi_1, \phi_2, \ldots, \phi_n))$ of such sets. Then we discuss in Section 3 the extent to which existing philosophical accounts of technical functions provide already means for carrying out the analysis and how these accounts may in turn be affected by the analysis. In Section 4 we focus on mereology and in Section 5 we consider engineering work on functional decompositions and illustrate how this may interact with philosophical research on the topic.

2 FUNCTIONAL ORGANISATION AND FUNCTIONAL COMPOSITION

In the previous section we introduced functional decomposition as a relation $\mathit{Decomp}(\Phi,\ \mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n))$ that is to be read as that the subfunctions $\phi_1,\ \phi_2,\ \ldots,\ \phi_n$ ordered by the organisation $\mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n)$ provide a decomposition of the function Φ. For defining this relation more formally, we here describe functional descriptions in general and more systematically. We start by introducing organisations $\mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n)$ of functions, then we introduce compositions $\mathit{Comp}(\mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n))$ of such organisations of functions, and finally we define decompositions $\mathit{Decomp}(\Phi,\ \mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n))$ in terms of such compositions.

Let, firstly, $\boldsymbol{F}$ be the set of all functions of technical systems. This set contains thus both the overall function Φ and the subfunctions $\phi_1,\ \phi_2,\ \ldots,\ \phi_n$ in the case of a decomposition $\mathit{Decomp}(\Phi,\ \mathit{Org}(\phi_1,\ \phi_2,\ \ldots,\ \phi_n))$.

Define, secondly, "$\rightarrow$" as a relation of *functional ordering* between two functions ϕ and ϕ' in $\boldsymbol{F}$ that expresses that functional output of ϕ is functional input to ϕ'. Functional input and output of a function are for now primitive terms; in Section 5 we discuss an engineering approach to functional decomposition in which this input and output consist of flows of materials, signals and energies, yet other choices — the functional input and output may consist of forces and fields — are not ruled out. But, having this approach in mind, we assume that a functional ordering $\phi \rightarrow \phi'$ implies the temporal ordering that ϕ is not later than ϕ'. The ordering is in general neither symmetric nor reflexive, but for specific functions ϕ and ϕ' it may hold that $\phi \rightarrow \phi'$ and $\phi' \rightarrow \phi$, or that $\phi \rightarrow \phi$: a force can be functional output of ϕ and functional input to ϕ', while the reaction force is output of ϕ' and input to ϕ; heat may be functional output of ϕ and functional input to other functions but also input to ϕ itself. A functional ordering $\phi \rightarrow \phi'$ is represented by an ordered pair $\langle \phi, \phi' \rangle$ that belongs to the Cartesian product $\boldsymbol{F} \times \boldsymbol{F}$.

Define, thirdly, a *functional organisation* $Org(\phi_1, \phi_2, \ldots, \phi_n)$ of a set $\{\phi_1, \phi_2, \ldots, \phi_n\}$ of functions as a set $\{\phi_i \rightarrow \phi_j\}$ of functional orderings of $\phi_1, \phi_2, \ldots, \phi_n$. A functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ is thus a, not necessarily connected, network of orderings between the functions $\phi_1, \phi_2, \ldots, \phi_n$, as depicted in the figures 1 and 2. A functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ is represented by a set $\{\langle \phi_i, \phi_j \rangle\}$ of ordered pairs from the Cartesian product $\boldsymbol{F} \times \boldsymbol{F}$.

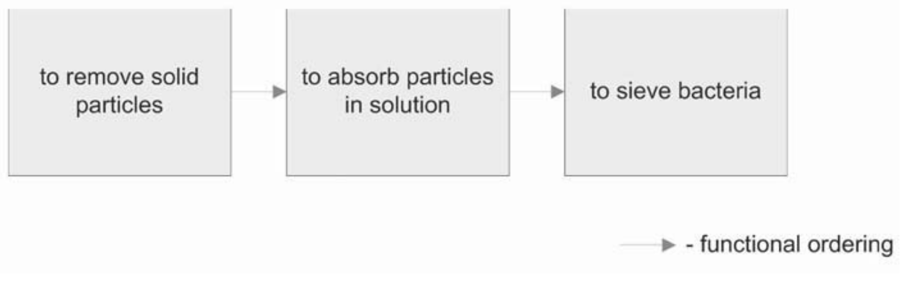

Figure 1. A linear functional organisation

Networks of organised sets $\{\phi_1, \phi_2, \ldots, \phi_n\}$ of functions in $\boldsymbol{F}$, like those depicted in figures 1 and 2, are in engineering taken as making up other functions Φ in $\boldsymbol{F}$. We capture this by defining, fourthly, *functional composition* $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$ which maps the functions $\phi_1, \phi_2, \ldots, \phi_n$ in their organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ to this function Φ, that is, $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$. Formally, the general notion of functional composition is represented by a set of ordered pairs $\langle \{\langle \phi_i, \phi_j \rangle\}, \Phi \rangle$ that contains a set $\{\langle \phi_i, \phi_j \rangle\}$ of ordered functions from $\boldsymbol{F} \times \boldsymbol{F}$ and a function Φ defined on $\boldsymbol{F}$.

Yet, functional composition *Comp* does not map every set $\{\langle \phi_i, \phi_j \rangle\}$ in $\boldsymbol{F} \times \boldsymbol{F}$ onto another function Φ in $\boldsymbol{F}$. Engineering constraints rule out some ordered pairs $\langle \phi_k, \phi_l \rangle$ as representing possible functional orderings $\phi_k \rightarrow \phi_l$, and if a set

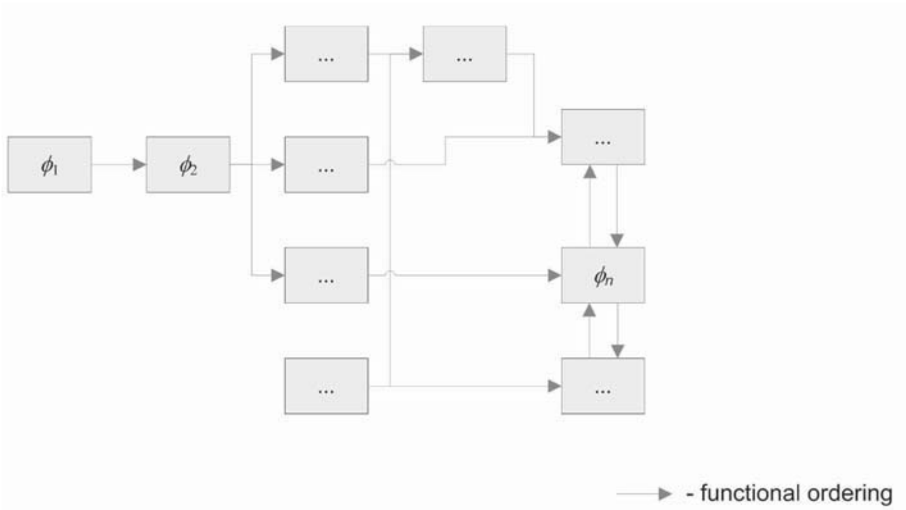

Figure 2. A more complex functional organisation

$\{\langle\phi_i, \phi_j\rangle\}$ is containing one or more of such impossible orderings, then this set $\{\langle\phi_i, \phi_j\rangle\}$ neither represents a functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$, nor is mapped by *Comp* to another function in $\boldsymbol{F}$. A general example of an engineering constraint on functional orderings $\phi_k \to \phi_l$ is that ϕ_k is not later than ϕ_l since then functional output of ϕ_k cannot possibly be functional input to ϕ_l. And in the approach in which functional inputs and outputs are flows of materials, signals and energies, one can derive more specific constraints: if, for instance, ϕ_k has electricity as its functional output, it cannot provide input to a function ϕ_l that has only water as its functional input.

With functional composition defined, we are now able to define the general notion of functional decomposition as a relation $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ represented by a set of ordered pairs $\langle\Phi, \{\langle\phi_i, \phi_j\rangle\}\rangle$ such that a function Φ from $\boldsymbol{F}$ occupies their first argument place and a set $\{\langle\phi_i, \phi_j\rangle\}$ of ordered functions from $\boldsymbol{F}\times\boldsymbol{F}$ occupies the second argument place. For this relation it holds that $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ if and only if $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$. In other words, the relation *Decomp* is the inverse relation to *Comp*. A more verbose reading of this decomposition relation $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ is thus that the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ ordered by the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ provide a decomposition of the function Φ, since the composition $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$ of $\phi_1, \phi_2, \ldots, \phi_n$ ordered by $Org(\phi_1, \phi_2, \ldots, \phi_n)$ is equal to Φ.

We assume that functional composition $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$ is unique in the sense that a set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ organised by $Org(\phi_1, \phi_2, \ldots, \phi_n)$ composes one function Φ. Yet we assume also that other compositions $Comp(Org(\phi'_1, \phi'_2, \ldots, \phi'_{n'}))$ may compose that same function Φ as well; engineering practices provide evidence for this latter assumption. Hence, a given function Φ may be decomposable in more than one way, meaning that $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ should indeed not be read as that the set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ ordered by $Org(\phi_1, \phi_2, \ldots, \phi_n)$ is the unique decomposition of Φ. In sum, both functional composition *Comp* and functional decomposition *Decomp* are relations, but only the former is in the mathematical sense a function.

2.1 Technical systems

With the above concepts and definitions, the analysis of functional descriptions is given in primarily functional terms; only in the functional ordering relation between two functions ϕ and ϕ' there is a reference to the temporal ordering: ϕ is not later than ϕ'. The functions in functional descriptions are, however, functions of technical systems, and we now broaden our analysis to those systems to make the concepts and definitions more tangible.

Let s be the system that is described by the function ϕ, and adopt the convention that $s_1, s_2, \ldots, s_n$ and S are the systems described by the functions $\phi_1, \phi_2, \ldots, \phi_n$ and Φ, respectively.[12] In general a function ϕ does not single out uniquely one system s due to the underdetermination that exists between functional and structural descriptions of systems; a function ϕ rather fixes a set of entities $\{s\}$ that have that function: the function *to conduct an electric current* can be performed by a copper wire, but also by other technical systems. Conversely, for a system s there exists in general a set $\{\phi\}$ of functions it can perform: a copper pipe can conduct electricity but also guide a fluid or gas. A technical system s can, moreover, be an *endurant* or a *perdurant*;[13] up to now we sloppily alluded to this distinction by distinguishing between technical systems that are objects and those that are processes, respectively. A consequence of these observations is that a functional organisation of a set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ does not in general translate straightforwardly into an associated spatiotemporal organisation of a set of systems $\{s_1, s_2, \ldots, s_n\}$, and *vice versa*. There exist, for instance, functions ϕ that can describe both endurants and perdurants: the function *to prevent depletion of soil*, for instance, describes fertilizers (endurants) *and* rotary crop systems (perdurants).[14] A functional organisation of a set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ containing

[12] In the examples discussed in this chapter the entities $s_1, s_2, \ldots, s_n$ are all different systems: system s_i is thus by our convention straightforwardly described by the function ϕ_i. More complex cases are possible as well. Two functions ϕ_j and ϕ_k, may, for instance, describe the same system, which then implies that the associated systems s_j and s_k are one and the same.

[13] We use the terms "endurant" and "perdurant" in the standard philosophical sense, i.e., an endurant is an entity that persists through time by being wholly present at more than one time and a perdurant is entity that persists through time by having different temporal parts or stages at different times (cf., for instance, [Lewis, 1986]). Nonetheless, we do not want to engage in the debate between threedimensionalism and fourdimensionalim, in which these terms are applied. Without accepting or rejecting the actual existence of endurants and perdurants, we just provide a theoretically broad framework, which makes room for both types of entities.

[14] One can distinguish in general three types of functions: functions ϕ that single out only endurants $\{s\}$ (the function *to support the back and bottoms of humans*, for instance, seems to

such a "hybrid" function, clearly defines spatiotemporal organisations of the set of systems $s_1, s_2, \ldots, s_n$, that may be mutually quite different. And two ordered or unordered functions ϕ_1 and ϕ_2 may be performed by one system (the two functions *to conduct an electrical current* and *to guide water* may be performed by one single copper pipe), meaning that the functional organisation may even be lost all together.

For analysing relationships between functional organisations of sets of functions and the associated organisations of the sets of technical systems, we continue by considering four special cases defined by the ontological opposition between endurants and perdurants. We sketch how in these examples the functional organisation of the functions $\phi_1, \phi_2, \ldots, \phi_n$ is related to the spatiotemporal organisation of the systems $s_1, s_2, \ldots, s_n$. In the first two cases the systems in the set $\{s_1, s_2, \ldots, s_n\}$ are all endurants and each s_i is functionally described by one separate function ϕ_i from the set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$. In the first case the function Φ that composes $\phi_1, \phi_2, \ldots, \phi_n$ in their functional organisation, i.e., $\Phi = Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$, describes a system S that is an endurant as well; in the second case this function describes a system S that is a perdurant. In the third and fourth case the systems $\{s_1, s_2, \ldots, s_n\}$ are all perdurants, is each s_i functionally described by one separate function ϕ_i, and is the composite function Φ describing an endurant S or a perdurant S, respectively.

Table 1. The four special cases

	$s_1, s_2, \ldots, s_n$	S
Case 1	endurants	endurant
Case 2	endurants	perdurant
Case 3	perdurants	endurant
Case 4	perdurants	perdurant

So, let us start with considering the first two cases in which the functions $\phi_1, \phi_2, \ldots, \phi_n$ are all functions of different endurants $s_1, s_2, \ldots, s_n$. These endurants are spatially positioned relative to one another and this positioning determines which of the endurants $s_1, s_2, \ldots, s_n$ can physically interact with one another in a technological relevant way.[15] There may, for instance, be a technologically relevant

single out different chairs but not processes); functions ϕ that single out only perdurants (say, the function *to provide health care*); and functions for which the set $\{s\}$ contains both endurants *and* perdurants (*to prevent depletion of soil*, as argued in the main text). Further examples of the third type reveal also that a function ϕ of an endurant s may sometimes be reinterpretable as a function ϕ of a perdurant s' that takes place in that endurant s, and *vice versa*: the function *to tear down city walls* of the endurant "cannon", for instance, can be taken alternatively as a function of the perdurant "shooting cannon balls" with that cannon, and *vice versa*.

[15] Engineering determines what technologically relevant physical interactions are. In electrical engineering, electromagnetic interactions are relevant, in mechanical engineering, action and reaction forces are relevant, and so on.

interaction between the endurants s_1 and s_2, but not between s_1 and s_3, and so on. Let us now capture this spatial positioning by the set of unordered pairs $\{\{s_i, s_j\}\}$ of endurants that do interact and call this the *spatial organisation* of the endurants $\{s_1, s_2, \ldots, s_n\}$. Assuming that the functional output of one function ϕ can only be the functional input to another function ϕ' through physical interactions between the systems s and s' that these functions are describing, this spatial organisation of $\{s_1, s_2, \ldots, s_n\}$ puts a direct constraint on the functional ordering of the functions $\phi_1, \phi_2, \ldots, \phi_n$ and thus on their functional organisation: $Org(\phi_1, \phi_2, \ldots, \phi_n)$ can consist of only a set $\{\phi_i \rightarrow \phi_j\}$ of functional orderings for which holds that for each element $\phi_i \rightarrow \phi_j$ the pair $\{s_i, s_j\}$ is an element of the spatial ordering of the endurants $\{s_1, s_2, \ldots, s_n\}$.

The system S that is functionally described by the function $\Phi{=}Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$, is now in its turn either an endurant or a perdurant. If S is an endurant, it is to be taken as an endurant that contains the physical composite of the endurants $s_1, s_2, \ldots, s_n$ in their spatial organisation.[16] If S is a perdurant, it is to be taken as a perdurant in which an endurant that contains that physical composite participates.

An example of the first case is the composition of the three functions *to attach to the seabed* (ϕ_1), *to fix distance* (ϕ_2) and *to attach to the vessel* (ϕ_3) of the three endurants “anchor”, “rope” and “knot”, yielding the function *to fix the location of a vessel in open sea* of an endurant “anchoring system”. The right spatial positioning of the anchor, rope and knot, allows action and reaction forces between the anchor and rope, and between the rope and the knot. Hence the spatial organisation of these endurants is captured by the set {{anchor, rope}, {rope, knot}}. The functional organisation $Org(\phi_1, \phi_2, \phi_3)$ of the three functions is $\{\phi_1 \rightarrow \phi_2, \phi_2 \rightarrow \phi_1, \phi_2 \rightarrow \phi_3, \phi_3 \rightarrow \phi_2\}$ with the functional inputs and outputs all forces, and this organisation satisfies the constraint that the spatial organisation puts on it. The endurant S consisting of anchor, rope and knot in their spatial organisation can perform the function $Comp(Org(\phi_1, \phi_2, \phi_3)) = \Phi$ of fixing a ship.

An example of the second case is the composition of the functions *to remove solid particles* (ϕ_1), *to absorb particles in solution* (ϕ_2) and *to sieve bacteria* (ϕ_3) of the different reservoirs s_1, s_2 and s_3 (which are assumed to be endurants) part of a wastewater plant, yielding the function *to purify water* of the perdurant “ water treatment” (i.e., the process) that is performed by the plant. Assuming a linear spatial positioning of the reservoirs, fluids can flow from s_1 to s_2, and from s_2 to s_3 letting the spatial organisation be equal to $\{\{s_1, s_2\}, \{s_2, s_3\}\}$. The functional organisation of the three functions is $\{\phi_1 \rightarrow \phi_2, \phi_2 \rightarrow \phi_3\}$ (see also Figure 1) with the functional inputs and outputs all fluids in different phases of cleansing, and this organisation satisfies the constraint that the spatial organisation puts on it. The perdurant S is the water treatment process that takes place in the reservoirs

[16] One may assume that the endurant S is just the physical composite of the endurants $\{s_1, s_2, \ldots, s_n\}$. This assumption is however challenged by the occurrence of all types of back-up systems and other safety systems in technical systems. It thus seems more tenable to hold that the physical composite of $\{s_1, s_2, \ldots, s_n\}$ is part of S.

in their linear spatial organisation and this process can perform the composite function Φ to purify water.

In the third and fourth case that we consider, the functions $\phi_1, \phi_2, \ldots, \phi_n$ are all functions of different perdurants $s_1, s_2, \ldots, s_n$. These perdurants are spatiotemporally positioned relative to one another and this positioning again determines which pairs of perdurants can physically interact with one another in a technological relevant way. If two perdurants s_i and s_j take place simultaneously and in one another's vicinity, such an interaction can take place from s_i to s_j and froms_j to s_i. Such bidirectional interactions are represented in the *spatiotemporal organisation* of the perdurants $s_1, s_2, \ldots, s_n$ by unordered pairs $\{s_i, s_j\}$, similar to the interactions between the endurants discussed in the first two cases. If a perdurant s_k takes place before another s_l, interaction is possible only from s_k to s_l. These unidirectional interactions are particular to sets of perdurants and we represent them by ordered pairs $\langle s_k, s_l\rangle$. The spatiotemporal organisation of the perdurants $s_1, s_2, \ldots, s_n$ thus has the form $\{\{s_i, s_j\}, \langle s_k, s_l\rangle\}$. Assuming again that the functional output of one function can only be the functional input to another function through a physical interaction, this spatial organisation of $\{s_1, s_2, \ldots, s_n\}$ puts again a constraint on the functional organisation of these functions: $Org(\phi_1, \phi_2, \ldots, \phi_n)$ can consist of only a set $\{\phi_i \to \phi_j\}$ of functional orderings for which holds that for each element $\phi_i \to \phi_j$ the pair $\{s_i, s_j\}$ or $\langle s_i, s_j\rangle$ is an element of the spatiotemporal ordering of the perdurants $\{s_1, s_2, \ldots, s_n\}$.

The system S that is functional described by the function $\Phi = Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$ is an endurant or a perdurant. If S is an endurant, it is to be taken as an endurant which participates (possibly only partially) in the perdurants $s_1, s_2, \ldots, s_n$ in their spatiotemporal organisation. If S is a perdurant, it is to be taken as a perdurant that consists of the perdurants $\{s_1, s_2, \ldots, s_n\}$ in their spatiotemporal organisation.

An example of the third case is the composition of the functional organisation of the functions *to spin* (ϕ_1), *to collect water* (ϕ_2), *to produce hot dry air* (ϕ_3) and *to vent humid air* (ϕ_4) of the four processes s_1, s_2, s_3 and s_4 that perform them in a drying machine (the endurant S), yielding the function Φ *to dry clothes* of that machine. The four processes can take place simultaneously, giving a spatiotemporal organisation containing every possible combination $\{s_i, s_j\}$. The functional organisation $Org(\phi_1, \phi_2, \phi_3, \phi_4)$ is $\{\phi_1 \to \phi_2, \phi_3 \to \phi_4\}$ with the functional inputs and outputs all consisting of water, and this organisation satisfies clearly the constraint that the spatiotemporal organisation of the processes $\{s_1, s_2, s_3, s_4\}$ puts on it. The endurant S "drying machine" can perform the function $Comp(Org(\phi_1, \phi_2, \phi_3, \phi_4)) = \Phi$ of drying clothes.
indent An example of the fourth and final case is the composition of the functions *to emit radio waves with a specific frequency* (ϕ_1), *to detect radio waves with the same frequency* (ϕ_2) and *to display the direction and the delay of the reflected waves* (ϕ_3) of processes s_1, s_2 and s_3 (perdurants) that take place in the radar equipment, yielding the function *to detect plane positions* of a process S (also a perdurant) that includes these three (sub)processes $\{s_1, s_2, s_3\}$. If the

processes s_1, s_2 and s_3 take place one after the other, their spatiotemporal organisation is given by $\{\langle s_1, s_2\rangle, \langle s_2, s_3\rangle\}$. The functional organisation $Org(\phi_1, \phi_2, \phi_3)$ is $\{\phi_1 \to \phi_2, \phi_2 \to \phi_3\}$ with the functional inputs and outputs all signals, and this organisation satisfies the constraint that the spatiotemporal organisation of the perdurants $\{s_1, s_2, s_3\}$ puts on it. The perdurant S containing the three processes s_1, s_2 and s_3 can perform the function $Comp(Org(\phi_1, \phi_2, \phi_3)) = \Phi$ of detecting the positions of planes.

These four special cases suggest the following generalisation. For a functional description of the technical systems $\{s_1, s_2, \ldots, s_n, S\}$ by means of the functions $\{\phi_1, \phi_2, \ldots, \phi_n, \Phi\}$, where $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$ and where the technologically relevant physical interactions between the systems $\{s_1, s_2, \ldots, s_n\}$ are given by the spatiotemporal organisation $\{\{s_i, s_j\}, \langle s_k, s_l\rangle\}$, the following constraint on the functional organisation holds: $Org(\phi_1, \phi_2, \ldots, \phi_n)$ can consist of only a set $\{\phi_i \to \phi_j\}$ of functional orderings for which holds that for each element $\phi_i \to \phi_j$ the pair $\{s_i, s_j\}$ or the pair $\langle s_i, s_j\rangle$ is an element of the spatiotemporal ordering of the perdurants $\{s_1, s_2, \ldots, s_n\}$. This constraint is most probably not the only one that is possible or reasonable. One can envisage also that in engineering one wants to limit the number of technological relevant (and irrelevant) physical interactions between the systems $\{s_1, s_2, \ldots, s_n\}$ that are not required by the functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$; such 'spurious' interactions may, for instance, lead to unintended effects. Moreover, the systems $\{s_1, s_2, \ldots, s_n\}$ are all systems that have by definition functions, meaning that the endurants and perdurants part of S that do not have functions are ignored; including such non-functional systems in the description will most probably again amount to all kinds of constraints.

3 FUNCTIONAL DESCRIPTIONS AND PHILOSOPHICAL ACCOUNTS OF TECHNICAL FUNCTIONS

Philosophy has, as we have noted, produced a number of accounts that spell out what it means to describe individual technical objects or processes functionally.[17] These accounts may be taken as a starting point for the analysis of functional descriptions, and this analysis can in turn be seen as a next step in the development of the accounts. We present here three archetypical approaches towards technical functions[18] and assess them for their ability to be developed to also describe more complex functional descriptions. The analysis of functional descriptions becomes as such also a criterion for judging the versatility of the existing accounts of technical functions to incorporating engineering activities such as functional decomposition.

In the first approach functions of technical systems are analysed in terms of the *intentions* of their designers or of their users: the function of a system is taken as

[17]See Preston's chapter *Philosophical Theories of Artifact Function* in this Handbook.
[18][Houkes and Vermaas, 2009].

the capacity or goal for which it is designed or for which it is used. This approach can be called the *intentionalist approach*. An example is the account of technical functions by Karen Neander in which "the function of an artifact is the purpose or end for which it was designed, made, or (minimally) put in place or retained by an agent" [1991a; 1991b, p. 462]. The second approach emphasises the physical structure of technical systems and identifies the functions of parts of a system as the parts' actual physical capacities that, together, causally contribute to a physical capacity of that system. This approach can be called the *causal-role approach* (the *systems functions approach* may be an alternative) and it was Robert Cummins [1975] who put it forward in detail. The third approach towards technical functions is one that defines functions relative to long-term developmental histories of technical systems. It takes distance from individual design processes of technical systems and individual uses, and focuses instead on their cultural dissemination. It identifies the function of a system with the capacity for which the system is *reproduced* for a longer period of time. This final approach can be called the *evolutionist approach*.[19] The example is now Ruth Garrett Millikan's notion of proper function [1984; 1993].

Of these three approaches especially the causal-role approach provides more than just an analysis of what it means to describe individual systems functionally. In this approach a set of actual capacities $c_1, c_2, \ldots, c_n$ of a set of parts $s_1, s_2, \ldots, s_n$ of a technical system that, together, causally contribute to a physical capacity C of that system, are all simultaneously taken as the functions $\phi_1, \phi_2, \ldots, \phi_n$ of the parts $s_1, s_2, \ldots, s_n$. Hence, in this approach one has at once a functional description that consists of multiple functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ and of a spatiotemporal organisation of the parts $s_1, s_2, \ldots, s_n$ that puts constraints on the functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ of these functions. Moreover, the interactions between the parts $s_1, s_2, \ldots, s_n$ required for letting the capacities $c_1, c_2, \ldots, c_n$ causally contribute to the physical capacity C, provides more definite information about the functional organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$.[20]

Conversely, functional descriptions containing the functions $\phi_1,\ \phi_2,\ \ldots,\ \phi_n$ and Φ with $Comp(Org(\phi_1,\ \phi_2,\ \ldots,\ \phi_n))=\Phi$, and describing sets of technical systems $\{s_1,\ s_2,\ \ldots,\ s_n,\ S\}$, plausibly fit the causal-role account. In this account the functions $\phi_1,\ \phi_2,\ \ldots,\ \phi_n,\ \Phi$ single out capacities $c_1,\ c_2,\ \ldots,\ c_n,\ C$ of the systems $s_1,\ s_2,\ \ldots,\ s_n,\ S$ for which has to hold that, firstly, the systems $s_1,\ s_2,\ \ldots,\ s_n$ are parts of S and, secondly, the capacities $c_1,\ c_2,\ \ldots,\ c_n$ contribute causally to the capacity

[19] The evolutionist approach has its origin in the analysis of biological functions and theories that fall under this approach are called *etiological theories* in that domain. In Preston's chapter in this handbook, the evolutionist approach falls under the heading of *non-intentionalist reproduction* views.

[20] In the causal-role approach a system s can have more than one function: s may have a capacity c as its function ϕ since c causally contributes to a capacity C of a system S, s may have a capacity c', different to c, as its function ϕ' since c' causally contributes to a capacity C' of a system S', and so on. We here ignore questions about the relations between these multiple functions and consider only the organisation of the functions that parts $s_1, s_2, \ldots, s_n$ have on the basis of their causal contributions to one capacity C of one system S.

C. On the basis of the discussion of the four cases of functional composition given in section 2.1, the first condition plausibly holds and the second also although it introduces an explicit commitment that functions compose overall functions due to causal contributions. Consider, for instance, the example of the composition of the three functions *to attach to the seabed*, *to fix distance* and *to attach to the vessel* of anchor, rope and knot, yielding the function *to fix the location of a vessel in open sea* of an anchoring system. This example fits the causal-role approach, since the anchor, rope and knot are parts of the anchoring system and the capacities corresponding to their functions are causally contributing to the capacity "fixing the location of a vessel in open sea" of the anchoring system as a whole.

Intentionalist approaches, in which users determine by their intentions the functions of technical systems, provide less means to analyse functional descriptions; intentionalist approaches that put designers at centre stage in determining functions, fare better. A technical system that is used for a specific capacity can in a user-intentionalist approach be ascribed that capacity as a function. Yet, for also ascribing functions to parts of that system, one has to assume that these parts are also intentionally used for specific capacities. This latter assumption seems, however, in general less tenable. In the anchoring-system example, for instance, it can be maintained that the system as a whole is intentionally used to fix the location of a vessel in open sea, but it is less tenable to maintain that a sailor who is throwing out an anchor line, uses the anchor for its capacity to attach to the seabed, the rope for its capacity to fix distance, and the knot for its capacity to attach to the vessel. Hence, user-intentionalist approaches provide for descriptions consisting of single functions ascribed to single systems, but may fail to give more complex functional descriptions. A designer-intentionalist approach can create such complex functional descriptions, since it can be maintained that designers in addition to designing technical systems as wholes, also design their parts intentionally. In the anchoring-system example, for instance, it can be said that the system as a whole, and the anchor, rope and knot were designed for the capacities to fix the location of a vessel in open sea, to attach to the seabed, to fix distance and to attach to the vessel, respectively. A first conclusion about the intentionalist approach seems therefore that it should de-emphasise the relevance of user intentions in the determination of functions of technical systems, in favour of designer intentions: designer-intentionalist approaches seem better equipped to incorporate more complex engineering functional descriptions. The account of technical functions as put forward by Wybo Houkes and Pieter Vermaas,[21] is an example of a designer-intentionalist approach (it incorporates also elements of the causal-role and evolutionist approaches). In this account engineers can ascribe a capacity C as a function Φ to a technical system S as a whole, ascribe capacities $c_1, c_2, \ldots, c_n$ as functions $\phi_1, \phi_2, \ldots, \phi_n$ to parts $s_1, s_2, \ldots, s_n$ of S, and relate these functions [Vermaas, 2006]. The difference with the causal-role approach is that in the Houkes-Vermaas account the entities S and $s_1, s_2, \ldots, s_n$ need not actually have the capacities C and $c_1, c_2, \ldots, c_n$, respectively; the engineers need

[21] [Houkes and Vermaas, 2004; Vermaas and Houkes, 2006].

only to have justified beliefs about S and s_1, s_2, …, s_n having these capacities and about the capacities c_1, c_2, …, c_n contributing to the capacity c.

Conversely, functional descriptions containing the functions $\{\phi_1, \phi_2, \ldots, \phi_n, \Phi\}$ with $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))=\Phi$, and describing sets of technical systems $\{s_1, s_2, \ldots, s_n, S\}$, plausibly fit designer-intentionalist approaches, since, for instance, such functional descriptions can be taken as supported by the beliefs of designers.

For evaluating the construction of functional descriptions in evolutionist approaches, again a distinction is to be made between approaches that put users at centre stage and those that favour designers. Let a designer-evolutionist approach be one in which a function ϕ of a technical system s is the capacity c for which designers reproduce s's, say by including s's repeatedly in their designs as systems that can perform the capacity c.

Such evolutionist approaches can provide for functional descriptions like functional compositions. Anchor systems are repeatedly included in designs of ships for the capacity to fix the location of a vessel in open sea, so this capacity becomes the anchor system's function Φ in a designer-evolutionist approach. And also anchors, ropes and knots are repeatedly included in designs for the capacities to attach to the seabed, to fix distance and to attach to the vessel, respectively, so also these capacities become the functions ϕ_1, ϕ_2 and ϕ_3 of the anchor, rope and knot part of the anchoring system.

In a user-evolutionist approach, in which a function ϕ of a technical system s is the capacity c for which users (let) reproduce s's by using s's repeatedly for the capacity c, more complex functional descriptions may in general be harder to create. The reason for this is that it is less tenable to maintain that users (let) reproduce parts s of larger systems S for a specific capacity c. Consider again the anchoring system S and the anchor s_1, rope s_2 and knot s_3. The reproduction of the whole system S due to user demands does now not necessarily imply that the parts s_1, s_2 and s_3 are also reproduced due to user demands. Due to the underdetermination that exists between functions and systems, a technological innovation may make that at some point in time some of the parts of the anchoring system are changed. The rope s_2 may, for instance, be changed into a chain s'_2 and the knot s_3 by a welded joint s'_3. In an extreme case there may exist for a specific system S with a fixed function Φ a number of different sets $\{s_1, s_2, \ldots, s_n\}$, $\{s'_1, s'_2, \ldots, s'_n\}$, … of parts by means of which S can be constructed, showing that reproduction of S need not imply reproduction of its parts. This conclusion may be rejected by taking systems consisting of different parts also as different systems: one could take the position that the anchoring system consisting of the anchor s_1, chain s'_2 and welded joint s'_3 is a different system S' as compared to the anchoring system S consisting of the anchor s_1, rope s_2 and knot s_3. By that position reproduction of the old anchoring system S still implies reproduction of the anchor s_1, rope s_2 and knot s_3 as well, and reproduction of the new anchoring system S' implies reproductions of the anchor s_1, chain s'_2 and welded joint s'_3. For anchoring systems this position may be tenable, but from an engineering perspective this position is less plausible for more complex technical systems. In technical systems like cars and industrial plants, simple parts like wires, pipes and switches can typically be replaced by alternative parts, and this replacement does not immediately turn those systems from an engineering point of view into new systems. The conclusion that this reproduction of technical systems S due to user demands does not in general imply that the parts of S are reproduced by those user demands as well, may also be rejected by noting that in the case of parts the users should be identified with the designers of the system S: user demands make that whole systems are reproduced and make that designers reproduce the parts of those systems. This position, however, turns a user-evolutionist approach towards functions into a designer-evolutionist approach. Hence, our first conclusion about evolutionist approaches is that they should de-emphasise the relevance of the reproduction of systems due to user demands in the determination of their functions, in favour of the reproduction of those systems by designers.[22]

Conversely, functional descriptions containing the functions $\{\phi_1, \phi_2, \ldots, \phi_n, \Phi\}$ with $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))=\Phi$, and describing sets of technical systems $\{s_1, s_2, \ldots, s_n, S\}$, plausibly fit designer-evolutionist approaches. In those approaches the systems $\{s_1, s_2, \ldots, s_n, S\}$ have the their functions $\{\phi_1, \phi_2, \ldots, \phi_n, \Phi\}$ only if designers have reproduced for a longer period those systems for the capacities corresponding to their functions $\{\phi_1, \phi_2, \ldots, \phi_n, \Phi\}$, and the fact that designers did so, provides support to the conclusion that the functions $\phi_1, \phi_2, \ldots, \phi_n$ compose in their functional organisation to Φ.

Our assessment of the three philosophical approaches towards technical functions is clearly a preliminary one that needs to be developed. This development is bound to correct our conclusions that the causal-role approach is suitable to an analysis of functional decomposition, and that the intentionalist and evolutionist approaches are so only if they de-emphasise the role of user intentions and of user demands in their respective analyses of functions of technical systems.

4 THE FUNCTIONAL PART-WHOLE RELATIONSHIP AND MEREOLOGY

Functional descriptions, and specifically functional decompositions $Decomp(\Phi, Org(\phi_1, \phi_2, \ldots, \phi_n))$ and compositions $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))=\Phi$, amount to a part-whole relation directly on the level of functions, where the overall function Φ takes the role of whole and the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ take the role

[22]Another attempt to save user-evolutionist approaches may consist of an argument that draws on the distinction between "selection for" and "selection of" as made in [Sober, 1993] in the context of biological evolutionary theory. One may assume that the evolution of technical systems can be described by a technological version of this theory and then argue that user demands amounts to a selection of systems S "for" the capacities corresponding to their functions Φ, which in turn amounts to a selection "of" the parts $s_1, s_2, \ldots, s_n$ with the capacities corresponding to their functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$. This argument seems, however, again blocked by the underdetermination phenomenon that a particular system S can in principle be constructed from different sets $\{s_1, s_2, \ldots, s_n\}$, $\{s'_1, s'_2, \ldots, s'_n\}$, ... of parts: a selection of S "for" the capacity corresponding to its function Φ does not unambiguously amount to a selection "of" a specific set of parts $s_1, s_2, \ldots, s_n$.

of parts. This analysis of functional descriptions faces, however, a serious problem with the understanding of the term "part". If we understand the relation of parthood in the sense establish by standard mereology, then one can derive a number of consequences for subfunctions and overall functions that at least at first sight are incompatible with the engineering understanding of functional descriptions. In this section we present this problem and discuss possible solutions. First, we briefly sketch one of the possible axiomatisations of mereology. Then we expose the consequences involved in expressing the relation of being a subfunction in terms of the mereological relation of parthood. Finally, we try to investigate whether the current state of the art in philosophy and logic provides with some feasible means to work around the problem.

So let us start with mereology itself. We cannot provide here a comprehensive exposition of the formal theory of mereology.[23] The following axiomatisation, which is one among a number of equivalent systems, is given just for the sake of reference.

Alfred Tarski formalised the standard mereology originally formulated by Stanisław Leśniewski (cf. the English translation of his works in [Srzednicki and Rickey, 1984]) by means of one primitive term: the relation of (improper) parthood denoted here by "$\leq$", where "$x \leq y$" is to be read as "x is an *improper part* of y". Tarski's axiomatisation contains two axioms:

(4.1) If $x \leq y$ and $y \leq z$, then $x \leq z$.

(4.2) If $X \neq \emptyset$, then there exists exactly one x such that x SUM X.

The expression "x SUM X" means that x is the *mereological sum* of the set X. The relation SUM is defined as follows:[24]

(4.3) $x \text{ SUM } X \equiv \forall y \in X\ (y \leq x) \wedge \neg\exists y\ (y \leq x \wedge \forall z \in X y \int z)$.

(4.4) $x \int y \equiv \neg\exists z(z \leq x \wedge z \leq y)$.

The expression "$x \int y$" is to be read as: x is *disjoint from* y. The complement of the relation of disjointness is the relation of *overlap*, which is usually denoted by "$\bigcirc$".

The problem now arises when we assume that axioms 4.1 and 4.2 apply to the domain of technical functions. If mereology is to be considered as a useful tool in analysing the part-whole relationship between subfunctions and overall functions, we must assume some kind of correspondence between this relationship and mereological terms. A suitable candidate mereological term for establishing this correspondence seems to be the relation SUM.

(4.5) The functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ are subfunctions of the function Φ iff Φ SUM $\{\phi_1, \phi_2, \ldots, \phi_n\}$.

[23]An interested reader may consult [Simons, 1987] and [Casati and Varzi, 1999].
[24]Cf. [Tarski, 1956].

There are, however, a number of reasons to reject this choice. First, one can argue that SUM is not the proper relation to connect subfunctions and overall functions. Axiom 4.2 guarantees that for any non-empty set of functions, there exists the mereological sum of these functions. By means of 4.5 one thus has for any set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ an overall function Φ that has them as subfunctions, meaning that for any set of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ there is a function Φ that can count as the composition of these functions. Yet, one can envisage sets of functions for which this will not be the case. Consider, for instance, the set {*to maintain a pressure of 1 atmosphere in vessel* x *at time* t, *to maintain a pressure of 2 atmosphere in vessel* x *at time* t}; by their intentional meaning it seems impossible to compose these two functions.[25] Using the terminology defined in Section 2, we can explicate this fact by saying that for some sets of functions there does not exist any organisation by which they can be composed: an organisation of the function *to maintain a pressure of 1 atmosphere in vessel* x *at time* t and the functions *to maintain a pressure of 2 atmosphere in vessel* x *at time* t does not exist since these two functions cannot be temporally ordered one after the other, nor ordered simultaneously.

Second, also if sets of functions $\{\phi_1, \phi_2, \ldots, \phi_n\}$ properly compose overall functions Φ by SUM, there may be scientific and engineering reasons to nevertheless deny that they define reasonable compositions. The functions in the set {*to cool*, *to allow a magnetic degree of freedom*, *to process a login request signal*, *to sand*} may be taken as composing the overall function *to smooth surfaces*. But that composition seems also technologically nonsensical by the spurious first three elements. The reason for this *embarrass de richesse* is the fact that mereology lacks the conceptual tools needed to express any kind of scientific or engineering constraint or standard. Again, using the terminology defined in Section 2, we can formulate this second fact by saying that for some sets of functions specific organisations are from a scientific or engineering point of view (better) ruled out.

Third, Axiom 4.3 guarantees that any non-empty set of functions composes exactly one other function. Consequently, if there are two engineering models in which the same set of subfunctions composes different functions due to different orderings between the subfunctions, the embedding of the functional part-whole relationship into mereology by 4.5 turns out to be inadequate. That such sets exist was briefly indicated at the beginning of section 1.1. Let ϕ_1 be the function *to heat with 150 degrees centigrade*, let ϕ_2 be *to keep the temperature fixed*, and let ϕ_3 be *to cool with 150 degrees centigrade.* If these functions are performed sequentially in the order given, they may be taken as composing the function Φ_1 *to bake,* but if they are performed in reverse order, they compose the overall function Φ_2 *to refrigerate.* Again, the source of this incongruity seems to be the

[25] [Simons, 2006] is one of the recent attempts at restricting the general principle of composition. Simons proposes to restrict this principle to the equivalence classes of mereologically disjoint objects. That is to say, if X is an equivalence class of this kind, then there exists such x that x SUM X. For instance, if we define in the set of protons and neutrons the relation: x exchanges gluons with y, then this relation will yield the equivalence classes of protons and neutrons such that each such class compose a single nucleus.

fact that we cannot express in mereology any kind of order among subfunctions, whereas ordering seems vital to functional composition and was therefore part to our characterisation of it. Using the terminology defined in Section 2, we can formulate this consequence by saying that for some sets of functions there can exist more than one organisation by which the functions in these set compose mutually different overall functions: for the functions $\{\phi_1,\ \phi_2,\ \phi_3\}$ introduced above one has, for instance, $Org_1(\phi_1,\ \phi_2,\ \phi_3)$ given by the orderings $\{\phi_1 \rightarrow \phi_2,\ \phi_2 \rightarrow \phi_3\}$, which defines the composition $Comp(Org_1(\phi_1,\ \phi_2,\ \phi_3))=\Phi_1$, and $Org_2(\phi_1,\ \phi_2,\ \phi_3)$ given by $\{\phi_3 \rightarrow \phi_2,\ \phi_2 \rightarrow \phi_1\}$, which defines $Comp(Org_2(\phi_1, \phi_2, \phi_3)) = \Phi_2 \neq \Phi_1$.

In sum, 4.5 is not a plausible candidate for a conceptual bridge between mereology and the functional part-whole relationship. Now the problem with applying mereology to functional descriptions is that there are not many alternatives to 4.5 available.[26] The above consequences derived from 4.5 suggest replacing the SUM relation with a more flexible expressive composition relation since some sets of functions do not (reasonably) compose[27] whereas other sets of functions have more than one composition.

In a recent proposal to describe components of technical systems in mereological terms as given by Peter Simons and Charles Dement [1996] this flexibility may seem to be present.[28] Their proposal presupposes one of the strategies of reconciling mereology with the real world, consisting of proclaiming that besides the notion of parthood defined in standard mereology, there are a number of more specific relations of parthood, e.g., being a functional part or being a component (cf. [Casati and Varzi, 1999, pp. 33—36]). These more specific relations need not satisfy all the requirements imposed by Leśniewski on the general relation of parthood.

First, we need to emphasise that Simons and Dement focus on functional parts of technical systems and not on subfunctions part of overall functions. Thus, their theory applies to what we have called the functionally-defined structural part-whole relationship between physical systems.

Being in a seminal way sensitive to the gap between standard mereology and actual engineering, Simons and Dement suggest substituting the general notion of part with a more specific notion that would be applicable to technical systems. The latter notion is tensed: x is part of y at time t. The following axioms establish the formal properties of the relation that captures this specific notion:

(4.6) If x exists at time t, then x is part of x at t.

[26] The problems with applying mereology outside the domain of mathematics are well investigated (cf. Rescher [1955], Casati and Varzi [1999], Pribbenow [2002], Johansson [2004]). But, due to the fact that functional descriptions have not received much philosophical attention, there are not yet solutions available that deal specifically with the problems associated with applying mereology to functional descriptions.

[27] [Simons, 2006] takes this approach in mereology, as is described in an above footnote.

[28] Other attempts at defining the notion of parthood suitable for technical systems may be found in [Tzouvaras, 1993], [Salustri and Lockledge, 1999], [Johansson, 2004] and [Vieu and Aurnague, 2005]. Nonetheless, none of these accounts concerns functional descriptions as discussed of this chapter.

(4.7) If x is part of y at time t, then x exists at t.

(4.8) If x is part of y at time t and y is part of z at t, then x is part of z at t.

(4.9) If x is a proper part of y at time t, then there exists z such that z is a proper part of y at t and x is disjoint from (i.e., does not overlap) z at t.

Simons and Dement define the relation of proper parthood and the relation of overlap in the following way.

(4.10) x is a proper part of y at time t iff x is part of y at t and y is not part of x at t.

(4.11) x overlaps y at time t iff there exists some z such that z is part of x at t and z is part of y at t.

If one ignores for a moment the tensed character of the relation parthood in question, the theory developed in [Simons and Dement, 1996] might be seen as a weaker version of standard mereology. In particular, we do not find here the counterpart of Axiom 4.2, so none of the aforementioned mereological paradoxes occurs here.

Simons and Dement claim further that the relation they define provides the most general framework for speaking about the mereology of technical systems. From a philosophical point of view, we may distinguish within this framework the following kinds of parts:

- assembly components, which are those parts that are manipulated as units during the processes of assembly or manufacturing,
- functional components, which are those parts that perform certain functions,
- maintenance components, which are those parts that are manipulated as units during the process of repairing,

and a number of other kinds.

The actual engineering practice involves however more specific notions. Simons and Dement draw our attention to three kinds of mereological structures related to three different engineering specifications of parts of technical systems. The *engineering bill of materials* represents the mereological components of the abstract physical architecture of a given system. The *manufacturing bill of materials* represents the mereological structure determined by a manufacturing schema for constructing the technical system in question. Finally, the *logistic bill of materials* specifies those components of the system that are salient for maintaining it in a state of readiness (cf. [Simons and Dement, 1996, pp. 268—271]).

Despite its conceptual complexity and despite the fact that it avoids the aforementioned paradoxes of standard mereology, Simons and Dement's theory of the mereological structure of technical systems is not meant to be applied to the modelling of functional part-whole relations, and seems also not to be applicable to it. Their theory does not make room for our notion of organisation or for some similar notion, which we believe is an indispensable aspect of any adequate conception of the functional part-whole relation. As a result, they can say neither that two parts of a technical system are sometimes not meaningfully or consistently combinable, nor that two subfunctions are sometimes not meaningfully or consistently combinable. And as a result, Simons and Dement cannot say that two parts of a technical system, or two subfunctions, are sometimes in multiple ways meaningfully and consistently combinable.

As we can see again, mereological language as available in the literature is not expressive enough to capture functional part-whole relationship. In our characterisation of functional descriptions we introduced the concept of organisation to create this expressiveness. A way to improve on the conceptual bridge 4.5 between the functional part-whole relationship and mereology, may now seem be one in which this concept is explicitly introduced into the bridge. Using the notation defined in Section 2, we can rewrite 4.5 as 4.5*.

(4.5*) $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$ iff Φ SUM $\{\phi_1, \phi_2, \ldots, \phi_n\}$.

4.5* clearly implies 4.12.[29]

(4.12) For *any* set of functions $\phi_1, \phi_2, \ldots, \phi_n$,

(i) there is an organisation *Org* of these functions such that there exists a function Φ, for which it holds that $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi$, and

(ii) for any two organisations of those functions Org_1 and Org_2, if $Comp(Org_1(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi_1$, and $Comp(Org_2(\phi_1, \phi_2, \ldots, \phi_n)) = \Phi_2$, then $\Phi_1 = \Phi_2$.

In general, 4.12 is false. As we argued above, for some sets of functions there do not exist organisations or reasonable organisations of the functions and for other sets of functions there exist more than one (meaningful) organisation relative to which they compose mutually different functions. Still, in some restricted domains of engineering the specific organisation of subfunctions might not be that relevant, i.e., it may not affect the overall functions to which these subfunctions compose. If one describes a domain of this sort, then 4.5 can be seen as a definition of the purely *mereological* type of functional part-whole relation (within this domain). The example of the purely temporally organised functions *to heat with 150 degrees centigrade*, *to keep the temperature fixed* and *to cool with 150 degrees centigrade*, shows that *temporal* functional part-whole relations are in general not of such a mereological type. But more special cases of such temporal functional part-whole relations, or of specific *spatial* functional part-whole relations may be. Obviously, all these types are borderline cases of the more general spatiotemporal part-whole relationship defined in Section 2 and this general relationship is not mereological in the standard sense.

[29]The implication from the left-hand side to the right-hand side in 4.5* is innocent; it is the reverse implication that should be blamed here.

5 AN ENGINEERING APPROACH TO FUNCTIONAL DECOMPOSITIONS

Engineering designing is, as we mentioned in the introduction, one of the engineering domains in which functional descriptions are in use. In the first conceptual phase of designing initial requirements about the product-to-be — user needs and additional specification about, for instance, safety — are translated into overall functions of the product and these functions are then by functional decompositions analysed in terms of series of subfunctions. Yet, the description of conceptual designing is far from being unambiguous: the initial design requirements are rarely standardised and often acknowledged to change during the unfolding of the design process, and the resulting overall functions and their decompositions are usually expressed in informal terms, not meeting rigorous constraints. As a result design methodologists interested in analysing and improving conceptual designing, are facing the problem how to define and represent functions and their decompositions more rigorously, a problem that has become increasingly important by the growing use of computers systems, such as CAD/CAM tools, to support engineering design. Among the different conceptual models that are devised to solve this problem,[30] we report here about what has become known as the *Functional Modelling* approach, since it provides relatively well-defined descriptions of functional decompositions, by which we can illustrate how engineering and philosophical research on functional decompositions can benefit from one another. The origin of this approach can be located in the fundamental work of Gerhard Pahl and Wolfgang Beitz [1996]; current research centres on a framework proposed by Robert Stone and Kristin Wood [2000]. We start by discussing Pahl and Beitz' original ideas of associating functions with *flows*, and then move to current research on what has become known as the *Reconciled Functional Basis*.[31]

Pahl and Beitz define a function as a *relation* between an input and an output of a technical system (under a specific goal) and claim that technical functions are derived from flows [1996, p. 31]. A *flow* is either a conversion of *material* (e.g., a chunk of clay being converted into a vase), a conversion of *energy* (e.g., electrical energy being converted into heat), or a conversion of *signal* (e.g., a safety buzz indicating the high pressure of a vapour).

Pahl and Beitz do not spell out what it means that functions are derived from flows. But in their definitions and examples they presuppose that any function boils down to a flow, for instance, when they refer to a function denoted by the expression "transfer torque", which clearly is a flow of torque.

[30] Research in design methodology is not converging to a single approach to functional descriptions or to functional decomposition. Authors use, and acknowledged to use, different notions of functions of technical systems and different ways of representing systems (see, e.g., [Umeda and Tomiyama, 1997; Chittaro and Kumar, 1998; Hubka and Eder, 2001]) and arrive at different models of, for instance, functional modelling (see, e.g., [Chandrasekaran, 2005; Far and Elamy, 2005; Van Eck *et al.*, 2007] for surveys).

[31] The functional modelling approach is also discussed in William H. Wood's chapter "Computational Representations of Function in Engineering Design" in this Handbook.

Pahl and Beitz then continue with observing that an overall function of a technical system can be complex or less complex in three senses: the relationships between the input and the output of the technical system may be relatively opaque or rather transparent; the underlying physical processes might be intricate or simple; and, finally, the number of assemblies and component might be higher or lower. They suggest that in the case of functions of high complexity it is advisable to decompose such functions into subfunctions for three reasons:

- to facilitate the subsequent search for design solutions,
- to obtain simple and unambiguous function structures, and
- to modularise the process of developing technical systems and their subsystems.

These subfunctions are in turn relations between inputs and outputs defined in terms of the three flows, and are linked to one another by a causal net of such flows. This structure of subfunctions and flows as a whole should now establish the same relation between an input and an output as the overall function it decomposes. Any two subfunctions that are linked together by a certain flow in such a causal net need to be "compatible" and all subfunctions of a given overall function need to be combined in a "meaningful" way. Although it is unclear what Pahl and Beitz mean with these terms, they observe that the relationship between subfunctions and overall function is very often governed by certain constraints, inasmuch as some subfunctions have to be satisfied before others. Moreover, the Pahl and Beitz methodology leads to the question of whether there is a level at which the decomposition stops or effectively stops. Pahl and Beitz consider five types of conversions that they take as reasonably not sub-dividable, being *to channel*, *to connect*, *to vary*, *to change* and *to store*. Together with their distinction between flows of *material*, *energy* and *signal*, one arrives at a taxonomy of 15 basic functions occurring at the lower level of functional decompositions. In later developments, topic of the next part of this section, especially this taxonomy has been changed.

Captured in our terminology, Pahl and Beitz arrive at functional decompositions $Decomp(\Phi, Org(\phi_1, \phi_2, \ldots, \phi_n))$, where Pahl and Beitz' overall function is Φ, the subfunctions are $\phi_1, \phi_2, \ldots, \phi_n$, and the causal net of flows defines the organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ of these subfunctions (each flow in the net from one subfunction ϕ_i to another ϕ_j, defines a functional ordering $\phi_i \to \phi_j$, and *vice versa*, meaning that $Org(\phi_1, \phi_2, \ldots, \phi_n)$ represents all connections in the net).

Compared to our analysis of functional descriptions as given in Section 2, Pahl and Beitz introduce a number of additional assumptions. It seems at first sight that in their methodology the overall function Φ and the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ in a functional decomposition are all typically describing systems S, s_1, s_2, $\ldots$, s_n that are perdurants, since conversions of flows refer to processes. However, the examples mentioned by Pahl and Beitz are functions of endurants — objects — and not of perdurants. That is, even if a function is a flow, i.e., a subtype of perdurant, this function is not a function of a perdurant; functions are special cases of perdurants that are ascribed to endurants.

Second, by taking functions as conversions of flows of materials, energies and signals, functions seem to have to comply with physical conservation laws for such flows. The conversion of a signal flow representing a small amount of energy, into a much larger electromagnetic energy flow, seems not to be a possible function in Pahl and Beitz' methodology.[32]

Finally, in a functional decomposition *Decomp*(Φ, *Org*(ϕ_1, ϕ_2, $\ldots$, ϕ_n)) the subfunctions ϕ_1, ϕ_2, $\ldots$, ϕ_n, are according to Pahl and Beitz ultimately not just any functions from the general set $\boldsymbol{F}$ of functions, but to be taken from the set of 15 conversions that are reasonably not sub-dividable. These subfunctions can thus only be *to channel*, *to connect*, *to vary*, *to change* and *to store* for materials, energies and signals.

When evaluating our analysis of functional descriptions with the methodology of Pahl and Beitz, a first remark can be that our functional ordering relation $\phi_i \rightarrow \phi_j$ may be (too) coarse-grained. In our analysis this relation holds already if there is "something" that can count as functional output of ϕ_i that is functional input to ϕ_j. In the Pahl and Beitz methodology this something is categorised as (types of) materials, energies and signals. This opens the possibility to develop our analysis by distinguishing between (associated) different types of functional ordering relations between functions. Other ways of developing our analysis can be drawn from the second and third additional assumptions sketched above. These assumptions are also made in more recent work in the Functional Modelling approach to functional decompositions, suggesting that our analysis of functional descriptions as given in Section 2 is too liberal: in order to let it cohere more with engineering work on functional descriptions, we should incorporate a requirement that functional descriptions comply with physical conservation laws and a requirement that all functions can be decomposed in terms of what can be called basic functions. Our analysis does not provide the means to formulate the first requirement; for incorporating the second requirement we can define a set $\boldsymbol{BF}$ of basic functions and the condition that for all functions Φ in $\boldsymbol{F}$ there exists a decomposition *Decomp*(Φ, *Org*($\phi_1, \phi_2, \ldots, \phi_n$)) with $\{\phi_1, \phi_2, \ldots, \phi_n\} \subseteq \boldsymbol{BF}$.

Taking some distance from the work of Pahl and Beitz, one can, however, doubt that especially the second additional assumption that functional descriptions have to comply with physical conservation laws holds for all engineering work on functional decomposition. Bell *et al.* [2007], for instance, accept functions that have a signal representing a small amount of energy as their input and a much larger

[32] That functions in the Functional Modelling approach have to comply with conservation laws is not explicitly said by Pahl and Beitz or in the key publications on the *Reconciled Functional Basis* discussed later in this section. Yet, examples of conversions of material and energy flows that are clearly violating conservation laws are hard to find, and the tracking of (conserved) flows seems to be an important device in developing functional decomposition in Functional Modelling. Modarres and Cheon [1999], however, make an explicit link between functions and conservation laws in (their work on) Functional Modelling.

electromagnetic energy flow as their output.[33] The physics that underlies such a function will clearly have to comply with conservation laws, but the input-output description of the function itself does not. The analysis of functional descriptions as given in Section 2, may therefore also be taken as a more general analysis, compared to which the additional assumptions in engineering methodologies for functional decomposition like the ones made by Pahl and Beitz can be analysed. This brings us to the benefits of philosophical research on functional descriptions to engineering: a philosophical analysis of such descriptions can help design methodologists with making their assumption explicit and with developing their work on functional decomposition. According to Pahl and Beitz the functions in decompositions are functions of endurants, but the examples given in Section 2.1 show that one can generalise functional decompositions to apply to also functions of perdurants. According to Pahl and Beitz functions comply with physical conservation laws, but this requirement may be dropped. And also the requirement that functions always have to be decomposable into functions from a set of basic functions may be questioned. One can, for instance, argue that this requirement has a context-dependent meaning. If functional decomposition is considered in the context of conceptual designing, this requirement may be that functions have to be decomposable into functions $\phi_1, \phi_2, \ldots, \phi_n$ from a set of easily solvable functions, that is, from a set of functions for which, given the technological state of the art, one has available or can find easily the systems $s_1, s_2, \ldots, s_n$ that can perform them (see also Section 1.1). Such a set of easily solvable functions varies with that technological state of the art. If, however, functional decomposition is considered in the context of engineering knowledge bases aimed at enhancing communication about functional descriptions among engineers, this requirement may have the form that functions are to be decomposable into functions $\phi'_1, \phi'_2, \ldots, \phi'_{n'}$ from a standardised set of functions, irrespectively of whether the functions in this set are easily solvable. Such a standardised set clearly should not vary (too much) over time.

5.1 The reconciled functional basis

A more recent research project that originates with the foundational work of Pahl and Beitz is the *Reconciled Functional Basis* project. This Reconciled Functional Basis (*RFB*, from now on) is the result of an effort towards establishing a standard taxonomy of basic technical functions (see, e.g., [Hirtz *et al.*, 2002]) by reconciling two previous taxonomies: the NIST taxonomy (cf. [Szykman, *et al.*, 1999]) and the older versions of the Functional Basis (developed in [Little *et al.*, 1997; Stone *et al.*, 1998; McAdams *et al.*, 1999; Stone *et al.*, 1999; Stone and Wood, 2000]). Each of these taxonomies is a result of empirical generalisation of engineering specifications.

RFB analyses the notion of a functional decomposition against the background of its taxonomy of functions, which is based on a taxonomy of flows. RFB modifies

[33] See, for instance, their model of a torch [Bell *et al.*, 2007, p. 401].

the meaning of the term "flow" since here "flow" does not mean "a process of flowing" (e.g., removing debris), but "a thing that flows" (e.g., debris).[34] More precisely speaking, in some papers, e.g., in [Stone and Wood, 2000] this term is used in both meanings, but the RFB taxonomy of flows is based on the latter sense. This shift in meaning is, to be sure, justifiable since it is hard to see how one might differentiate between a process of flowing and a function given the conception of Pahl and Beitz. The RFB whole taxonomy of flows is depicted in Table 2.

RFB also contains a three-layer classification of what are called basic functions. Each type of function is accompanied by a definition (in natural language), example, and a set of synonymous names. The basic functions are divided in a first layer into eight primary types. Then, some primary basic functions are divided into types of secondary basic functions, and some of these secondary basic functions are in turn divided into types of tertiary basic functions. The whole taxonomy is depicted in Table 3.

Of course, the RFB taxonomy of basic functions is not a model of functional decomposition. For instance, the fact that *Divide* and *Extract* are subtypes of *Separate* does not mean that the former are subfunctions of the latter. Moreover the basic functions are not functions in the sense the overall functions are, since the overall functions are (complex) modifications of specific input flows into specific output flows, whereas the basic functions are modifications generalised for the flows subjected. Hence, the basic subfunctions are in the RFB to be identified with basic functions operating on specific primary, secondary and tertiary flows.

In RFB a functional decomposition is a conceptual structure that consists of an overall function that is decomposed, its subfunctions into which the overall function is decomposed, the flows which are modified by the subfunctions, and a net that links these modifications in an ordered way.

The overall function to be decomposed is defined in terms of the flows it modifies, which are taken from the RFB taxonomy of flows. Each of its subfunctions is defined both in terms of the flows the respective subfunction modifies and in terms of its type of modification, which is taken from RFB taxonomy of basic functions. For instance, the overall function of a screwdriver, which is to tighten/loose screws, is defined by means of the following ten input flows and nine output flows (see also Figure 3).

- input flows for the function *tighten/loose screws*:
  - energy flows: *electricity, human force, relative rotation and weight*;
  - material flows: *hand, bit and screw*;
  - signal flows: *direction, on/off signal and manual use signal*;
- output flows for the function *tighten/loose screws*:
  - energy flows: *torque, human force, heat, noise and weight*;

[34] In engineering design the term "flow" is used in the specific sense in which it is roughly equivalent to the term "process".

Table 2. The RFB taxonomy of flows [Hirtz *et al.*, 2002]

Primary flow	**Secondary flow**	**Tertiary flow**
Material	Human	
	Gas	
	Liquid	
	Solid	Object
		Particulate
		Composite
	Plasma	
	Mixture	Gas-gas
		Liquid-Liquid
		Solid-solid
		Solid-liquid
		Liquid-gas
		Solid-gas
		Solid-liquid-gas
		Colloidal
Signal	Status	Auditory
		Olfactory
		Tactile
		Taste
		Visual
	Control	Analog
		Discrete
Energy	Human	
	Acoustic	
	Biological	
	Chemical	
	Electrical	
	Electromagnetic	Optical
		Solar
	Hydraulic	
	Magnetic	
	Mechanical	Rotational
		Translational
	Pneumatic	
	Radioactive/Nuclear	
	Thermal	

Table 3. The RFB taxonomy of functions [Hirtz *et al.*, 2002]

Primary functions	**Secondary functions**	**Tertiary functions**
Branch	Separate	Divide
		Extract
		Remove
	Distribute	
Channel	Import	
	Export	
	Transfer	Transport
		Transmit
	Guide	Translate
		Rotate
		Allow degree(s) of freedom
Connect	Couple	Join
		Link
	Mix	
Control magnitude	Actuate	
	Regulate	Increase
		Decrease
	Change	Increment
		Decrement
		Shape
		Condition
	Stop	Prevent
		Inhibit
Convert	Convert	
Provision	Store	Contain
		Collect
	Supply	
Signal	Sense	Detect
		Measure
	Indicate	Track
		Display
	Process	
Support	Stabilize	
	Secure	
	Position	

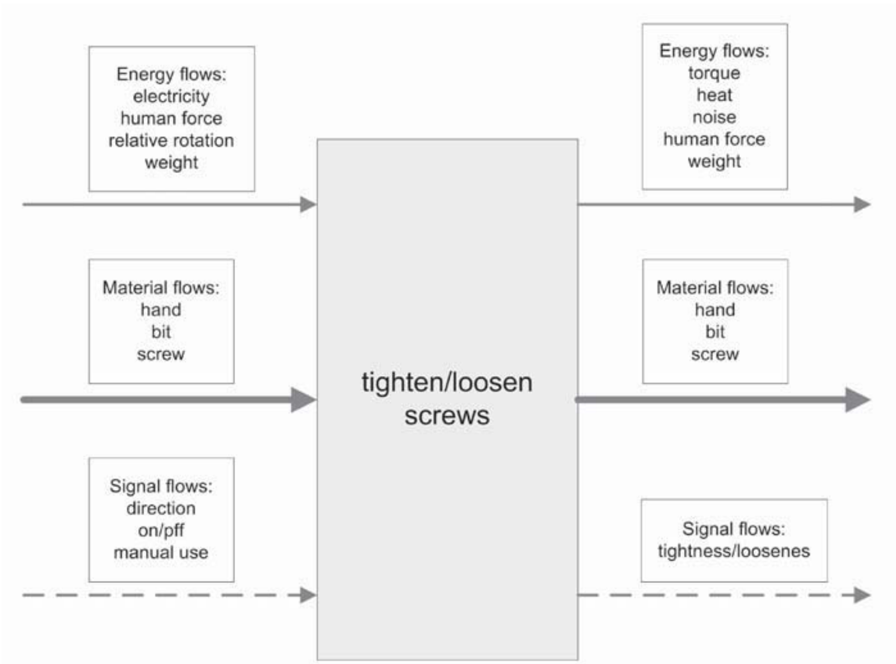

Figure 3. The RFB modelling of the overall function of a screwdriver [Stone and Wood, 2000, Fig. 2]

  - material flows: *hand, bit and screw*;
  - signal flows: *looseness/tightness*.

On the other hand, one of the subfunctions in the functional decomposition of this overall function *tighten/loose screws* is called *convert electricity to torque* (see Figure 4), which means that it is a function of the *convert*-type (cf. Table 3), and modifies one input flow to three output flows:

- input flows for the subfunction *convert electricity to torque*:
  - energy flows: *electricity*;
  - material flows: none;
  - signal flows: none.
- output flows for the subfunction *convert electricity to torque*:
  - energy flows: heat, noise and torque;
  - material flows: none;
  - signal flows: none.

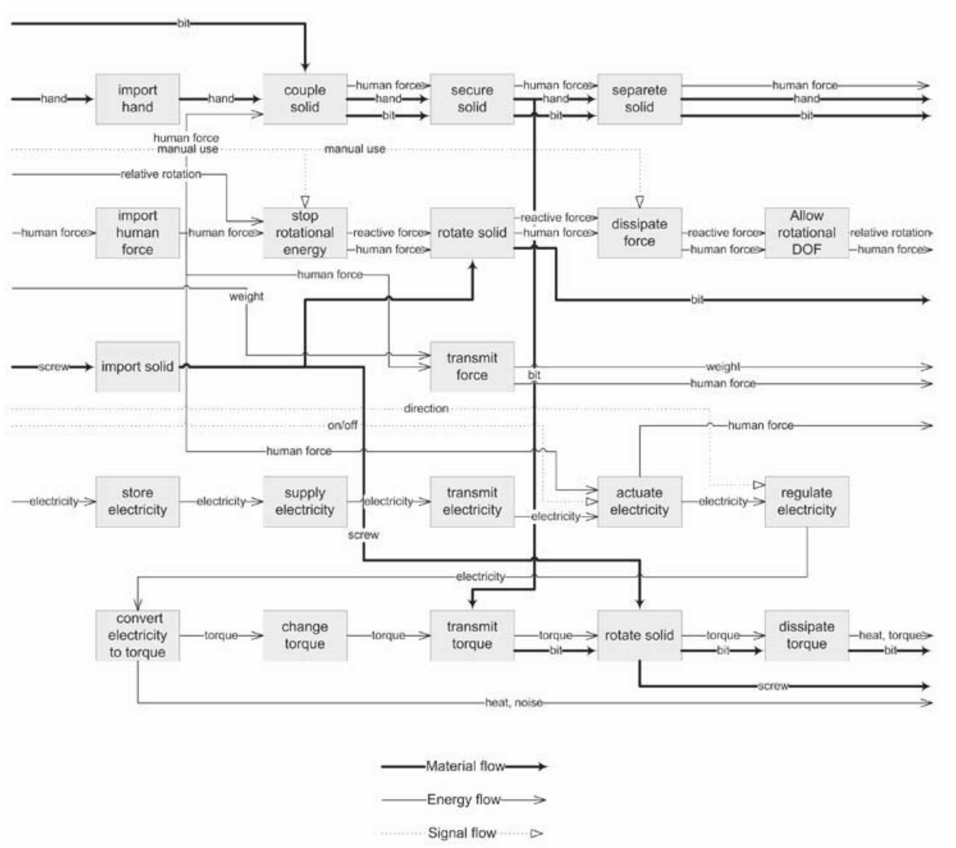

Figure 4. The RFB functional decomposition of a screwdriver [Stone and Wood, 2000, Fig. 4]

The task of a designer who performs a functional decomposition is to link any input flow of the overall function to be decomposed with some of the output flows. Any such link that starts with an input flow of the overall function and ends with one of its output flows is called a *function chain.* In RFB one distinguishes between two types of function chains: sequential and parallel. A function chain is *sequential* if it is ordered with respect to time, i.e., if any temporal permutation of its subfunction may in principle result in failing to perform the overall function. A *parallel* function chain is a fusion of sequential function chains that share one or more flows.

In RFB one assumes that each subfunction of an overall function to be performed by a technical system S is realised by a component of S; however, the relation between subfunctions and components is many-to-many, i.e., one subfunction may be realised by several components and one component may realise more than one subfunction.

The notion of functional decomposition developed within RFB plays an important role in what is called the concept generator, which is a web-based computational tool for enhancing conceptual design.[35] The concept generator is to present a designer with a number of different solutions to his or her design problem on the basis of previously developed (and stored) high-quality designs. One of the input data to be provided for this tool is a function chain for a product to be newly developed. The output solutions describe the design solution in terms of the technical systems whose descriptions are loaded into the knowledge base of the concept generator. The functional decomposition links the overall function established by the generator with the conceptual components that compose a general description of the product that is construed here as a solution of the initial design problem [Strawbridge *et al.*, 2002; Bryant *et al.*, 2004].

The RFB proposal adds precision and a wealth of empirical details to the methodology of Pahl and Beitz. Its explicit aim to contribute to the standardisation of conceptual models in engineering makes it even more valuable for specifically mereological analysis of functional modelling.

In our terminology, the overall function of an RFB functional decomposition $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ may be any function Φ but the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ are to be identified with RFB basic functions from Table 3 operating on specific RFB primary, secondary and tertiary flows from Table 2. The net of flows between the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ defines their organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$.

In RFB the overall functions Φ and the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$ in functional decompositions $Decomp(\Phi,\ Org(\phi_1, \phi_2, \ldots, \phi_n))$ may be describing systems S and $s_1, s_2, \ldots, s_n$ that are endurants and perdurants, but like in the methodology of Pahl and Beitz, again the additional assumptions are made that functions comply with physical conservation laws for flows, and that the subfunctions $\phi_1, \phi_2, \ldots, \phi_n$, are to be taken from a set of basic functions. A further additional assumption seems to be that the functional orderings $\phi_i \to \phi_j$ making up the organisations

[35] See http://function.basiceng.umr.edu/delabsite/repository.html.

$Org(\phi_1, \phi_2, \ldots, \phi_n)$ of the subfunctions, are always asymmetric: flows between two subfunctions in functional decompositions like depicted in Figure 4, always go in one direction. The benefit of philosophical research on functional descriptions to engineering can again lie in making these assumptions explicit and in challenging them. The requirement that functions always have to be decomposable into RFB basic functions operating on specific RFB flows introduces again a tension between the goal of functional decomposition to facilitate designing and to facilitate communication. Consider, for instance, the basic function *convert acoustic energy in electrical energy*. The identification of this basic function in a decomposition of an overall function may be useful to a shared understanding of this overall function but will not help designers to easily find a corresponding design solution. A requirement that subfunctions are only ordered in one direction may in turn be helpful in engineering for managing the flow of materials, energies and signals, but may also be revealed to be an unnecessary constraint to the decomposition of functions.

6 PROVISIONAL CONCLUSIONS

In this chapter we have introduced interrelated functional descriptions and specifically functional decompositions as a topic for philosophical analysis. We identified conceptual designing, reverse engineering and engineering knowledge bases as the engineering domains in which such functional descriptions are given. Special cases of interrelated functional descriptions that are important to engineering are functional decompositions: descriptions in which an overall function Φ of a technical system S is analysed in terms of a series of mutually ordered subfunctions ϕ_1, ϕ_2, $\ldots$, ϕ_n describing systems s_1, s_2, $\ldots$, s_n part of S. Features of interrelated functional descriptions that are of interest to philosophy are that they define two different part-whole relationships: a functionally-defined *structural* part-whole relationship by which the systems s_1, s_2, $\ldots$, s_n are part of the system S, and a *functional* part-whole relationship by which the functions ϕ_1, ϕ_2, $\ldots$, ϕ_n are part of the function Φ.

We introduced in Section 2 a series of formally defined relations for capturing interrelated functional decompositions. A *functional ordering* $\phi \rightarrow \phi'$ exists between two functions if functional output of ϕ is functional input to ϕ'. The *functional organisation* $Org(\phi_1, \phi_2, \ldots, \phi_n)$ of a set of functions ϕ_1, ϕ_2, $\ldots$, ϕ_n is defined as the set of (pair-wise) functional orderings that exists between these functions. *Functional composition* $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$ maps the functions ϕ_1, ϕ_2, $\ldots$, ϕ_n in their organisation $Org(\phi_1, \phi_2, \ldots, \phi_n)$ to another function Φ. *Functional decomposition* was finally taken as the inverse of composition and captured as a relation $Decomp(\Phi, Org(\phi_1, \phi_2, \ldots, \phi_n))$ for which holds that $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))=\Phi$. These relations were, moreover, illustrated with a series of cases and examples in which also the systems s_1, s_2, $\ldots$, s_n and S described by the functions ϕ_1, ϕ_2, $\ldots$, ϕ_n and Φ, respectively, were considered. The discussion of these cases/examples suggest that functional organisations in functional descriptions are constrained by the spatiotemporal ordering of the systems described: $\phi \rightarrow \phi'$ can hold only if there is a physical interaction from s to s'.

In this chapter we have, moreover, identified four areas in philosophy that may benefit from the analysis of functional descriptions: research on functions in philosophy of technology and in philosophy of biology, epistemology and mereology. Finally, we presented engineering work on functional decompositions, and considered how it can contribute to and benefit from our first exploration of functional descriptions. Here we sum up our findings, with the necessary provisos; since the analysis of engineering functional descriptions is a new topic in philosophy, this chapter can merely be an appetizer, shaped as well as limited by the directions we have chosen in our exploration, but hopefully rewarding nevertheless.

The first philosophical area that can benefit from the analysis of functional descriptions is research on the concept of technical functions in philosophy of technology. Philosophical accounts of technical functions may initially be taken as mere means to developing the analysis of functional descriptions. We now argued in Section 3 that of the three archetypical approaches towards such accounts, only Cummins' causal-role approach seems fully equipped to provide for such means; the other two approaches, that is, the intentionalist and the evolutionist ones, seem to be able to do so only if designers and not users are determining technical functions by their intentions or by reproduction, respectively. Hence, as its precondition, the analysis of functional descriptions requires that the role of users in the determination of technical functions in these latter two approaches is de-emphasised in favour of the role of designers.

Analyses of technical functions in philosophy of technology and of biological functions in philosophy of biology are often in interaction, for instance, by using them as contrasts to one another, or by attempting to unify them. By this interaction, it may be assumed that the analysis of functional descriptions in engineering may also have an impact on philosophy of biology. We have not elaborated on the possible results of this interaction.

In Section 4 we considered the area of mereology. We considered in particular the functional part-whole relationship between the functions $\phi_1, \phi_2, \ldots, \phi_n$ and the overall function Φ given by their composition $Comp(Org(\phi_1, \phi_2, \ldots, \phi_n))$. We have argued that this functional part-whole relationship cannot be understood with standard mereology, but requires a modelling in mereology that can accommodate organisations of the subfunctions.

In Section 5 we presented an engineering approach to functional decompositions, called functional modelling and described it in terms of the concepts part of our analysis of functional descriptions. Relative to this analysis functional modelling introduced a number of additional requirements. The more important ones were that functional descriptions have to comply with physical *conservation laws*, that there exists a set of *basic functions* into which other functional can be decomposed, and that functional ordering are always *asymmetric functional orderings*. We argued that these additional requirements could be incorporated into our analysis but could also be taken as assumptions in engineering approaches to functional descriptions that can be questioned, thus establishing the worth of philosophical analyses to engineering.

The remaining philosophical area to which the analysis of functional descriptions can contribute is epistemology. We have described in Section 1 the relations between functional descriptions, functional reasoning and explanation, and linked especially functional decomposition to the literature on mechanistic explanation, a link that establishes another relation between analysing functional descriptions and philosophy of biology. Yet, we did not delve deeper into these relations. One reason for not considering epistemology in detail is that we still have to acknowledge that the analysis of functional descriptions is currently in a first phase. We hope to have shown with our analysis and with the presentation of the engineering approach to functional decomposition that a philosophical analysis of engineering functional descriptions is feasible and beneficiary. Yet, our analysis is still a first step aimed primarily at clarity on conceptual and mereological aspects of functional descriptions, and — hopefully — opening the way to a versatile and more broader analysis of functional decomposition in the engineering sciences.

ACKNOWLEDGMENTS

Research by Pieter Vermaas was supported by the Netherlands Organization for Scientific Research (NWO).

BIBLIOGRAPHY

[Bechtel and Abrahamsen, 2005] W. Bechtel and A. Abrahamsen. Explanation: A mechanist alternative. *Studies in History and Philosophy of Biological and Biomedical Sciences*, 36, 421—441, 2005.

[Bell *et al.*, 2007] J. Bell, N. Snooke, and C. Price. A language for functional interpretation of model based simulation. *Advanced Engineering Informatics*, 21, 398—409, 2007.

[Bryant *et al.*, 2004] C. Bryant, D. McAdams, R. Stone, T. Kurtoglu, and M. A. Campbell. A computational technique for concept generation. In *Proceedings of IDETC/CIE 2005, Long Beach, CA*, paper no. DETC2005-85323, ASME, 2004.

[Casati and Varzi, 1999] R. Casati and A. Varzi. *Parts and Places*. MIT, 1999.

[Chakrabarti and Bligh, 2001] A. Chakrabarti and T. P. Bligh. A scheme for functional reasoning in conceptual design. *Design Studies*, 22, pp. 493—517, 2001.

[Chandrasekaran, 2005] B. Chandrasekaran. Representing function: Relating Functional Representation and Functional Modeling research streams. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 19, 65—74, 2005.

[Chittaro and Kumar, 1998] L. Chittaro and A. N. Kumar. Reasoning about function and its application to engineering, *Artificial Intelligence in Engineering*, 12, 331—336, 1998.

[Craver, 2001] C. F. Craver. Role functions, mechanisms, and hierarchy. *Philosophy of Science*, 68, 53—74, 2001.

[Craver and Bechtel, 2006] C. Craver and W. Bechtel. Mechanisms. In *The Philosophy of Science: An Encyclopedia*, S. Sarkar and J. Pfeifer, eds., pp. 469—478. Routledge, 2006.

[Cummins, 1975] R. Cummins. Functional analysis. *Journal of Philosophy*, 72, 741—765, 1975.

[de Ridder, 2006] J. de Ridder. Mechanistic artefact explanations. *Studies in History and Philosophy of Science*, 37, 81—96, 2006.

[de Ridder, 2007] J. de Ridder. *Reconstructing Design, Explaining Artifacts: Philosophical Reflections on the Design and Explanation of Technical Artifacts*. Simon Stevin Series in the Philosophy of Technology, Vol 4 (Delft University of Technology Ph.D. Thesis). 2007.

[Far and Elamy, 2005] B. H. Far and A. H. Elamy. Functional reasoning theories: Problems and perspectives. *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing*, 19, 75—88, 2005.

[Hirtz *et al.*, 2002] J. Hirtz, R. Stone, D. McAdams, S. Szykman, and K. Wood. A functional basis for engineering design: Reconciling and evolving previous efforts. *Research in Engineering Design*, 13, 65—82, 2002.

[Houkes, 2006] W. Houkes. Knowledge of artefact functions. *Studies in History and Philosophy of Science*, 37, 102—113, 2006.

[Houkes and Vermaas, 2004] W. Houkes and P. E. Vermaas. Actions versus functions: A plea for an alternative metaphysics of artefacts. *Monist*, 87, 52—71, 2004.

[Houkes and Vermaas, 2009] W. Houkes and P. E. Vermaas. Useful Material: *An Action-Theory of Artefacts and Their Functions*, Delft/Eindhoven Universities of Technology manuscript. 2009.

[Hubka and Eder, 2001] V. Hubka and W. E. Eder. Functions revisited. In *International Conference on Engineering Design,* ICED 01-C586/102, Glasgow, Scotland, August 21-23, pp. 69—76. 2001.

[Johansson, 2004] L. Johansson. On the transitivity of the parthood relations. In *Relations and Predicates*. H. Hochberg and K. Mulligan, eds., pp. 161—181. Ontos Verlag, 2004.

[Kitamura *et al.*, 2005/2006] Y. Kitamura, Y. Koji, and R. Mizoguchi. An ontological model of device function: Industrial deployment and lessons learned. *Applied Ontology*, 1, 237—262, 2005/2006.

[Lewis, 1986] D. Lewis. *On the Plurality of Worlds*. Blackwell, 1986.

[Little *et al.*, 1997] A. Little, K. Wood, and D. McAdams. Functional analysis: A fundamental empirical study for reverse engineering, benchmarking and redesign. In *Proceedings of the ASME Design Theory and Methodology Conference, Sacramento, CA*, paper no. 97-DETC/DTM-3879, ASME, 1997.

[Machamer *et al.*, 2000] P. Machamer, L. Darden, and C. F. Craver. Thinking about Mechanisms. *Philosophy of Science*, 67, 1—25, 2000.

[McAdams *et al.*, 1999] D. McAdams, R. Stone, and K. Wood. Functional interdependence and product similarity based on customer needs. *The Journal of Research in Engineering Design*, 11, 1—19, 1999.

[Millikan, 1984] R. G. Millikan. *Language, Thought, and Other Biological Categories: New Foundations for Realism*. MIT, 1984.

[Millikan, 1993] R. G. Millikan. *White Queen Psychology and Other Essays for Alice*. MIT, 1993.

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

[Neander, 1991a] K. Neander. Functions as selected effects: The conceptual analyst's defense. *Philosophy of Science*, 58, 168–184, 1991.

[Neander, 1991b] K. Neander. The teleological notion of "function". *Australasian Journal of Philosophy*, 69, 454—468, 1991.

[Pahl and Beitz, 1996] G. Pahl and W. Beitz. *Engineering Design: A Systematic Approach*. Springer, 1996.

[Pribbenow, 2002] S. Pribbenow. Meronymic relationships: From classical mereology to complex part-whole relations. In *The Semantics of Relationships: An Interdisciplinary Perspective*, R. Green, C. Bean and S. Myaeng, eds., pp. 35—50, Kluwer, 2002.

[Rescher, 1955] N. Rescher. Axioms for the part relation. *Philosophical Studies*, 6, 8–11, 1955.

[Salustri and Lockledge, 1999] F. Salustri and J. Lockledge. Towards a formal theory of products including mereology. In *Proceedings of the 12th International Conference on Engineering Design*, Birkhofer, Meerkamm, and Vajna, eds., pp. 1125–1130. Technische Universität München, 1999.

[Simons, 1987] P. Simons. *Parts: A Study in Ontology*. Clarendon, 1987.

[Simons, 2006] P. Simons. Real Wholes, Real Parts: Mereology Without Algebra. *Journal of Philosophy*, 103, 597–613, 2006.

[Simons and Dement, 1996] P. Simons and C. Dement. Aspects of the mereology of artifacts. In *Formal Ontology*, Volume 53 of *Nijhoff International Philosophy Series*, R. Poli and P. Simons, eds., pp. 255–276. Kluwer, 1996.

[Sober, 1993] E. Sober. *The Nature of Selection: Evolutionary Theory in Philosophical Focus*. University of Chicago Press, 1993.

[Srzedncki and Rickey, 1984] J. Srzednicki and V. Rickey, eds. *Lesniewski's Systems: Ontology and Mereology*. Kluwer, 1984.

[Stone and Wood, 2000] R. Stone and K. Wood. Development of a functional basis for design. *Journal of Mechanical Design*, 122, 359–370, 2000.

[Stone *et al.*, 1998] R. Stone, K. Wood, and R. Crawford. A heuristic method to identify modules from a functional description of a product. In *Proceedings of DETC98, Atlanta, GA*, paper no. DETC98/DTM-5642, ASME, 1998.

[Stone *et al.*, 1999] R. Stone, K. Wood, and R. Crawford. Product architecture development with quantitative functional models. In *Proceedings of DETC99, Las Vegas, NV*, paper no. DETC99/DTM-8764, ASME, 1999.

[Strawbridge *et al.*, 2002] Z. Strawbridge, D. McAdams, and R. Stone. A computational approach to conceptual design. In *Proceedings of DETC 02, Montreal*, paper no. DETC2002/DTM-34001, ASME, 2002.

[Szykman *et al.*, 1999] S. Szykman, J. Racz, and R. Sriram. The representation of function in computer-based design. In *Proceedings of the 1999 ASME Design Engineering Technical Conferences, Las Vegas, NV*, paper no. DETC99/DTM-8742, ASME, 1999.

[Tarski, 1956] A. Tarski. Foundations of geometry of solids. In *Logic, Semantics, Metamathematics*, A. Tarski, pp. 24–29, Oxford University Press, 1956.

[Tzouvaras, 1993] A. Tzouvaras. Significant parts and identity of artifacts. *Notre Dame Journal of Philosophy*, 34, 445–452, 1993.

[Umeda and Tomiyama, 1997] Y. Umeda and T. Tomiyama. Functional reasoning in design. *IEEE Expert*, 12(2), 42–48, 1997.

[van Eck *et al.*, 2007] D. van Eck, D. McAdams, and P. E. Vermaas. Functional decomposition in engineering: A survey. In *2007 ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference DETC2007, September 4-7, 2007, Las Vegas, NV*, paper no. DETC2007-34232, ASME, 2007.

[Vermaas, 2006] P. E. Vermaas. The physical connection: Engineering function ascriptions to technical artefacts and their components. *Studies in History and Philosophy of Science*, 37, 62–75, 2006.

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

[Vieu and Aurnague, 2005] L. Vieu. and M. Aurnague. Part-of relations, functionality and dependence. In *Categorization of Spatial Entities in Language and Cognition*. M. Aurnague, M. Hickmann and L. Vieu, eds., pp. 483–509. John Benjamins, 2005.

[Wimsatt, 2002] W. Wimsatt. Functional organization, analogy, and inference. In *Functions: New Essays in the Philosophy of Psychology and Biology*. A. Ariew, R. Cummins and M. Perlman, eds., pp. 173–221. Oxford University Press, 2002.

This page intentionally left blank