

# Incommensurability and Rationality in Engineering Design: The Case of Functional Decomposition

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## Abstract

In engineering design research different models of functional decomposition are advanced side-by-side. In this paper I explain and validate this co-existence of models in terms of the Kuhnian thesis of methodological incommensurability. I advance this analysis in terms of the thesis' construal of (non-algorithmic) theory choice in terms of values, expanding this notion to the engineering domain. I further argue that the (by some) implicated threat of the thesis to rational theory choice has no force in the functional decomposition case: co-existence of different models of functional decomposition is rational from an instrumental point of view. My explanation covers cases in which different models are advanced as means for the same objective. Such cases cannot be explicated with the explanatory construct of variety in objectives, as advanced in other analyses of co-existing conceptualizations in engineering.

**Keywords:** Functional decomposition, co-existence, methodological incommensurability, rationality

## 1. Introduction

Engineering design research on the modeling of technical functions provides what seems to be a striking contrast with research in the sciences. Whereas research in the sciences exhibits an orientation toward establishing (increasingly) unambiguous and commonly shared concepts<sup>1</sup> – and engages in debate about the adequacy of the conceptualizations proposed – functional modeling research does not, by and large, strive toward such conceptual uniformity nor engages in such debate. For instance, a key concept such as function lacks a uniform meaning in functional modeling research but, instead, is specific to particular modeling frameworks (cf. Erden et al. 2008). Models of functional decomposition, i.e., graphical representations of organized sets of functions, likewise come in a variety of flavors. And the majority of authors in functional modeling research accept this status quo. Some authors do aim to develop a common framework for functional modeling by means of specific functional conceptualizations (cf. Erden et al. 2008; Chandrasekaran 2005). Yet, most authors merely stick to advancing their favored frameworks without superiority claims over other ones.

Philosophical analyses of the co-existence of different conceptualizations in engineering explain the maintaining of this status quo as having instrumental value to engineering (cf. Bucciarelli 1994, 2003; Vermaas 2009; Van Eck 2010a). The analyses of Bucciarelli (1994, 2003) and Vermaas (2009) relate specific conceptualizations (as suitable means) to specific objectives, thus explaining (and validating) co-existence in terms of a variety of engineering ends. I have argued that the choice for and suitability of particular models of functional decomposition for particular objectives is influenced by whether or not specific design knowledge is employed in building these models, thus explaining (and validating) co-existence of different models in terms of variation in design knowledge employment (Van Eck 2010a). This latter analysis explains co-existence in informative fashion insofar as the knowledge used in building models does not contain or refer to a specific notion of function or specific functional decomposition model. When the knowledge used does already refer to a specific notion of function or specific model of

functional decomposition, the choice for (the construction of) specific models is obvious, but explication of such choices in terms of knowledge employment would become circular.

In this paper I further expand on the above analyses. Focusing on research on the modeling of functional decompositions, I argue that *different* functional decomposition models are also advanced in the engineering literature as means for the *same* objective. What to think of co-existence in this case? The questions that I will address are (i) why co-existence of different models obtains when the objective for which they are constructed is the same (rather than fixing a single best and commonly shared model) and (ii) whether the above implicated value of co-existence also holds in the case of co-existing and different models that are constructed for the same objective?

The previous analyses of co-existence that put forward variety in objectives as a central explanatory construct do not cover the above case(s) in which different functional decomposition models are used side-by-side as means toward the same objective. And neither does an explanation in terms of variation in design knowledge employment, since the models advanced in the above case are built using knowledge that already refers to specific models of functional decomposition. I will therefore follow a different tack to explain this case. I explain co-existence in this functional decomposition case in terms of the Kuhnian thesis of *methodological incommensurability*.<sup>2</sup> Key to this thesis is the notion that there is no neutral algorithm that governs scientific theory choice. Kuhn (1977) argued that theoretical disputes between advocates of rival frameworks cannot be solved by recourse to a neutral algorithm that dictates theory choice, since there is no commonly shared set of criteria or standards available on the basis of which such a choice can be forged. Kuhn (1977) pressed the point that such standards do not function as algorithmic rules by which one is able to determine theory choice but, rather, as *values* guiding such choices. I explain co-existence in terms of (and by expanding on) Kuhn's notion that one can explain divergence of theory choice in terms of variation in values. I argue that the choice for particular models of functional decomposition depends on the engineering values that are employed in choosing/evaluating them, and that these engineering values vary (and conflict) between modeling accounts. I conclude that the functional decomposition case exemplifies methodological incommensurability in the engineering domain.

Kuhn's analysis of values, in addition, led him to conclude that scientists' choice of (competing) theories can be considered rational. This conclusion has spawned extensive debate in philosophy of science. A key issue is whether in the absence of a commonly shared algorithm scientists' choice of theories can in fact be considered rational (Kuhn 1977). Thus, authors that accept variation in values are pressed to show that theory choice by means of values ensures the rationality of scientists' choice of theories (Worrall 1988; Sankey 1995, 2002). I will address this issue in the functional decomposition case. I argue that the choice and usage of different models by different engineers is rational from a practical point of view. I construct this argument along the lines of a position developed by Sankey (2002) in which he combines variation of values with a means-end analysis of values.

This paper is organized as follows. In section 2 I briefly present an overview of engineering notions of function and models of functional decomposition. Section 3 introduces the earlier analyses of co-existence. In section 4 I explain co-existence in terms of the thesis of methodological incommensurability. I argue for the rational grounds of co-existence in section 5. Section 6 concludes the paper.

## 2. Engineering Notions of Function and Functional Decomposition

The concept of function has a flexible meaning in the engineering domain. An analysis of Vermaas (2009) established three archetypical ones: behavior functions that refer to the desired behaviors of a device, effect functions that refer to the desired effects of the behaviors of a device, and purpose functions that refer to the purposes for which a device is designed. And, in addition, I identified a fourth (Van Eck 2009/2010): action functions that refer to intentional behaviors carried out by an agent using a device.

Behavior function descriptions characterize conversions of matter and/or energy in which physical conservation laws are taken into account, thus referring to physical behaviors. An electric screwdriver's function of 'converting electricity into torque and heat' (Stone and Wood 2000: 364), for instance, in which the energy of the electricity is supposed to equal the sum of the energies of heat and torque. Effect function descriptions also characterize (features of) behavior but do not take conservation laws into account, referring only to the desired effects of behavior. In case of a screwdriver's function, say, 'producing torque'. Purpose function descriptions refer to states of affairs intended by designers that are the final result(s) of behaviors. In the screwdriver case, say, 'having a rotational force down a shaft'.<sup>3</sup> Finally, action function descriptions are used to characterize user actions with a device; again in the screwdriver case, say, 'manually inserting a screw in a screw bit'.

These four notions of function are also described in engineering models of functional decomposition, i.e., graphical representations of organized sets of functions. Engineers put such models to a variety of uses. They use them, among others, in the conceptual phase of engineering designing to specify the desired functions of some artifact-to-be (Stone and Wood 2000; Chakrabarti and Bligh 2001); in the reverse engineering of existing artifacts to identify their functions (Otto and Wood 2001); and engineers use functional decomposition models to identify malfunctions of artifacts (Bell et al. 2007).

In this paper I consider three distinct engineering models of functional decomposition: a functional decomposition model of an organized set of behavior functions (behavior function  $fm_D$ ), a functional decomposition model of an organized set of effect functions (effect function  $fm_D$ ), and a functional decomposition model of an organized set of purpose functions (purpose function  $fm_D$ ).<sup>4</sup> Examples of such models are given in Figures 1, 2, and 3.

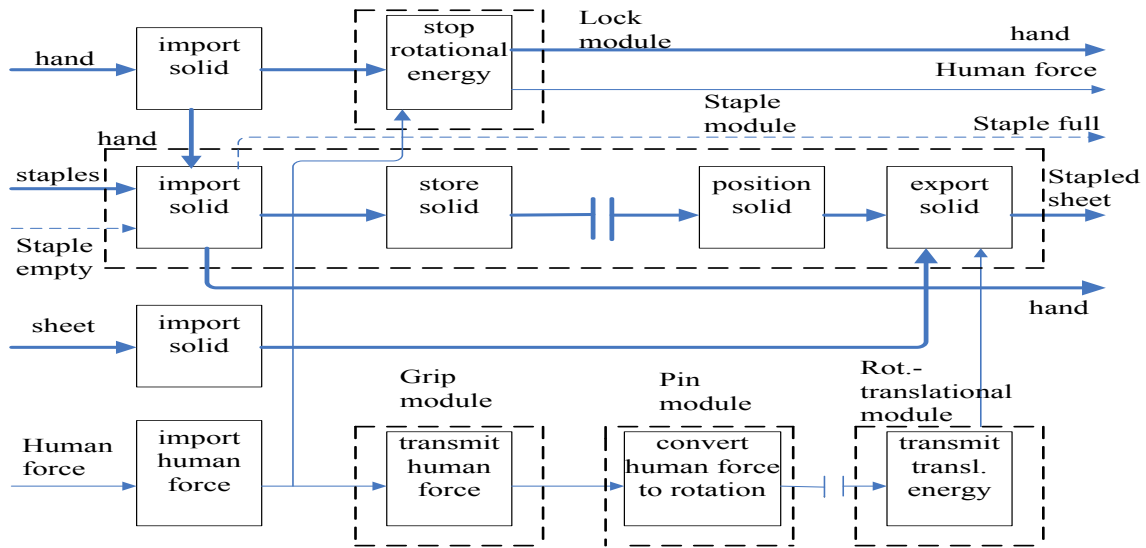


Figure 1. Behavior function  $f_{m_D}$  of a stapler (adopted from Stone et al. 2004)

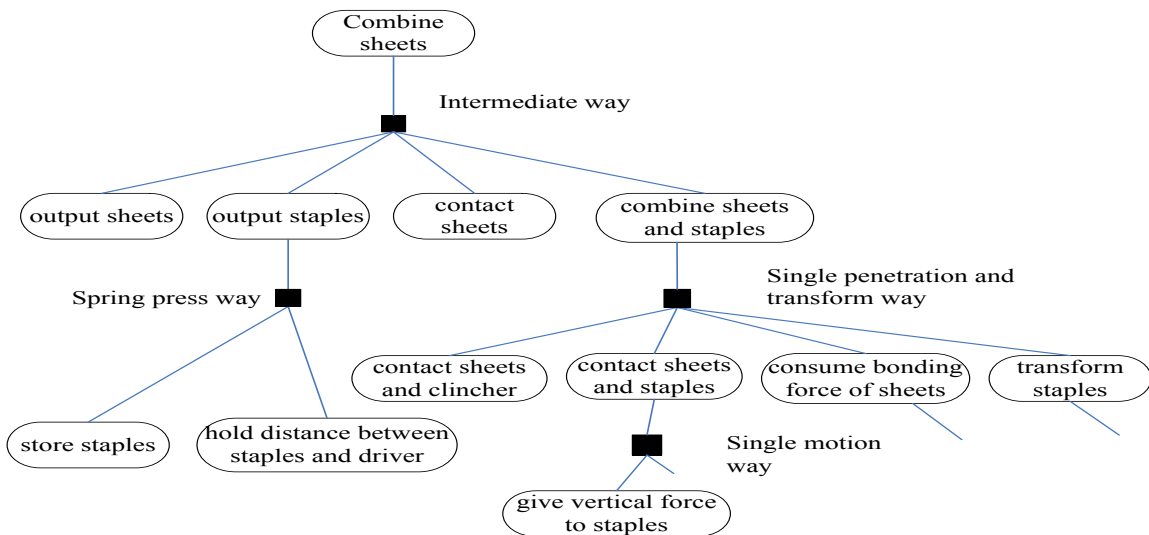
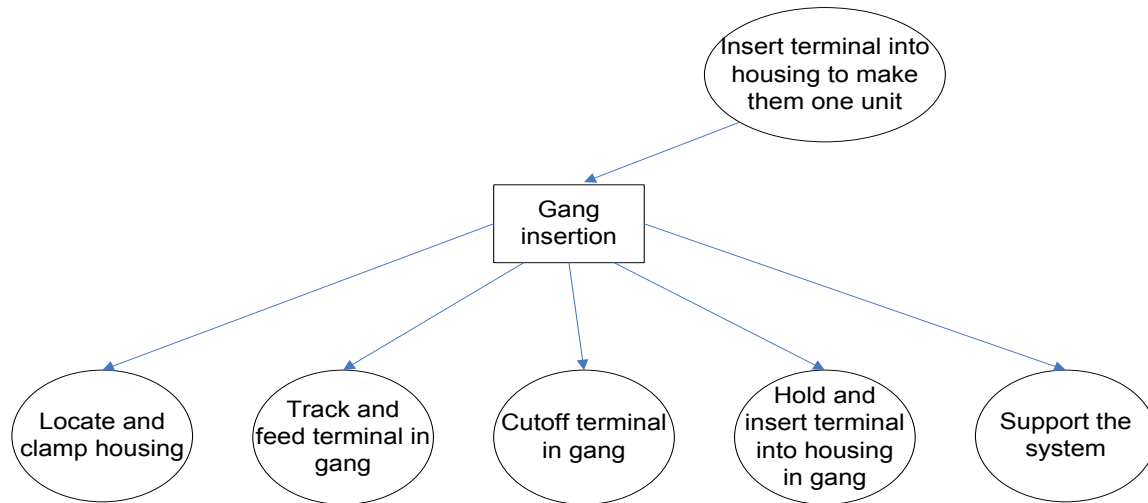


Figure 2. Effect function  $f_{m_D}$  of a stapler (adopted from Ookubo et al. 2007)



**Figure 3.** Purpose function  $fm_D$  of a terminal insertion device (adapted from Deng 2002)<sup>5</sup>

### 3. Explaining Co-existence by Variation of Objectives or Design Knowledge Employment

Philosophical analyses of the usage, side-by-side, of different conceptualizations explicate this co-existence as having instrumental value to engineering (cf. Bucciarelli 1994, 2003; Vermaas 2009; Van Eck 2010a). These analyses either relate specific conceptualizations (as suitable means) to specific objectives, or explicate the suitability of specific conceptualizations (as suitable means) to specific objectives in terms of design knowledge usage.

#### 3.1. Object Worlds

Based on analyses of several cases of actual engineering design practice, Bucciarelli advances the argument that engineers practice their trades in different “object worlds” (Bucciarelli 1994: 62; Bucciarelli 2003: 99). The notion of an object world(s) conveys: “the idea that different participants in design see the object of design differently depending upon their competencies, responsibilities and their technical interests” (Bucciarelli 2003: 99). Engineers from specific technical disciplines use conceptual frameworks in designing that are specific to their specialization; between technical disciplines there are differences in, amongst others, standards, regulations, mathematics, computer tools, and sketching and modeling tools (Bucciarelli 2003). Exponents from different disciplines hence will conceptualize an object of design in different ways. And they may also interpret a concept or notion that is shared across object worlds in different ways. As Bucciarelli (2003) illustrates: “the same object, say a prismatic bar, to the structural engineer is a cantilever beam while to the person responsible for ensuring that the system does not overheat, it is a radiating appendage” (99). These different conceptualizations have value since engineers from different object worlds work on different features of the object of design for which the adopted conceptualizations are useful (Bucciarelli 2003: 9). Phrased differently, these conceptualizations are useful for achieving specific objectives. For instance, the above conceptualization of a prismatic bar as a radiating appendage is useful when one’s objective is preventing a system to overheat, whereas a cantilever beam-conceptualization serves other ends.

Although conceptualizations between object worlds may be at variance in a given case of designing, requiring negotiation to arrive at design decisions (Bucciarelli 2003: 101), these co-

existing conceptualizations thus can be validated in terms of their being useful means to achieve a variety of objectives.

Whereas the above work of Bucciarelli validates co-existing conceptualizations between distinct engineering disciplines, the analyses of Vermaas (2009) and myself (2010a) support such conceptual divergence within an engineering discipline, to wit: functional modeling in electro-mechanical engineering.

### 3.2. Simplifying Full Descriptions of Technical Artifacts

Vermaas (2009) argues that specific meanings of the concept of technical function are used in engineering to advance specific descriptions of technical artifacts. Since these descriptions are all useful to engineering, he thus explains why the concept of function is used with more than one meaning in the field. He develops his analysis in terms of the notions of a full and a simplified description of a technical artifact. Vermaas identifies five key concepts in full descriptions of technical artifacts: *goals* of agents that refer to states in the world that agents desire to realize by using artifacts; *actions* that refer to intentional behaviors that agents carry out when using artifacts; *functions* that refer to desired roles played by artifacts; *behaviors* that refer to physicochemical state changes of artifacts; and *structures* that refer to the physicochemical materials and fields of artifacts, their configurations, and their interactions.

Vermaas (2009) argues that the flexible meaning of the concept of function affords different ways in which such full descriptions of technical artifacts can be simplified. Full descriptions in terms of the five key concepts are elaborate, and in particular engineering settings it makes sense to simplify them by “by-passing” one or more of the key concepts (Vermaas 2009: 2.119). Key to the analysis is that specific meanings of function are advantageous to specific by-passing simplifications. For instance, relative to the five key concepts, the concepts of action and behavior are by-passed in the account of Stone and Wood (2000) and the concept of function is used in its meaning of *desired behavior* (by specifying the role an artifact should play in terms of its behavior) to relate goals to structure. The concept of behavior is thus bypassed and the concept of function is instead used to refer to behavior(s). On the other hand, in the account of Lind (1994) the key concept of action is by-passed but not the concept of behavior. In this approach the concept of function is used in its meaning of *desired effect of behavior* (by specifying the role of the artifact in terms of the effects of the artifact’s behavior) to relate goals to behavior.

This analysis thus explains co-existing meanings of the concept of function (and the accounts in which these meanings are advanced) as useful for the advancement of different simplified descriptions of technical artifacts (objectives), all valuable to engineering.

### 3.3. $fm_D$ Choice and Knowledge Usage

In a similar vein, but focusing on the notion of design knowledge usage, I have argued that the choice for (constructing) particular  $fm_{DS}$  (behavior function  $fm_{DS}$ , effect function  $fm_{DS}$ , and purpose function  $fm_{DS}$ ) is influenced by whether or not particular design knowledge is employed in their construction. And that depending on the particulars of such design knowledge employment, particular models are best suited for achieving particular design objectives (Van Eck 2010a). I thus explained and defended the keeping of different  $fm_{DS}$  side-by-side (and the accounts in which they are advanced) in engineering design in terms of variation in design knowledge employment.

Among others, I considered  $fm_{DS}$  that are used to support the objective of innovative design, characterized as the designing of new artifacts that have potentially novel (combinations of) function-structure connections (e.g. Pahl and Beitz 1988; Stone and Wood 2000). Pahl and Beitz (1988) and Stone and Wood (2000) explicitly do not employ known function-structure connections (nor behavior-structure connections) in the construction of  $fm_{DS}$ , but establish such function-structure mappings after the completion of  $fm_{DS}$ . I argued that since known function-structure connections are not taken into account in the construction phase, behavior function  $fm_{DS}$  are best suited for the above objective since behavior function descriptions (which may include effects) are detailed enough to support the selection of (potentially novel) structures after the model is constructed. Purpose function  $fm_{DS}$  and effect function  $fm_{DS}$ , instead, are too coarse-grained to allow the selection of (potentially novel) structures in any precise way, when existing knowledge on function-structure connections is not considered in the construction phase of such models. The use of such models, skipping reference to behaviors and effects in purpose function  $fm_{DS}$  and to behaviors in effect function  $fm_{DS}$ , does not give (in a precise manner) those (potentially novel) structures that are suitable to achieve the functions of an artifact-to-be. For instance, a car's headlight effect-function "light on" may be suitable to select well-known structures such as an incandescent lamp or halogen one, but without a desired behavioral specification, the choice for, say, a more recent LED lamp (which differs in its behaviors by which the effect "light on" results) is less obvious.

On the other hand, I argued that other  $fm_{DS}$  get favored when their construction is based on employing known (and required) behavior-structure relations of an existing artifact. For instance, for the objective of design analysis, characterized as verifying whether the functions of an artifact are achieved by the behaviors of the artifact in the intended manner,  $fm_{DS}$  that are constructed based on known behavior-structure relations are used (e.g. Lind 1994; Bell et al. 2007). Given that both behavior and structure of an artifact are known, effect function  $fm_{DS}$  are suited for verifying whether the behaviors exercised by structures achieve (in the intended fashion) the functions that are desired. Using a purpose function  $fm_{DS}$ , instead, skipping reference to effects, does not give the precision to ascertain whether or not the functions are indeed manifested *in the intended way* by the behaviors of the artifact. For instance, the purpose function "illumination in a room" may be sufficient for determining whether the behavior of the artifact implements this function. Yet, it is not suited to verify whether the behavior of the artifact implements this function in the intended way. In contrast, an effect function description, say, "switch on-light on", is suited for verifying whether the behavior of the artifact implements this function in the intended way: say, the switch might be "off" while the light is still on. Such a failure goes undetected with the purpose function description "illumination in a room" (more elaborate behavior function  $fm_{DS}$  may also do the trick, but seem unnecessarily complex). Hence, given that behavior and structure of an artifact are known, effect function  $fm_{DS}$  are best suited for verifying whether the functions of an artifact are achieved by the behaviors of the artifact in the intended manner.

My analysis, like the ones of Bucciarelli (1994) and Vermaas (2009), shows the instrumental value of maintaining co-existence, in casu of different  $fm_{DS}$ : depending on the specifics of the design knowledge employed, particular models are best suited for achieving particular objectives.<sup>6</sup> This explanation however holds (in informative fashion) for certain cases only. That is, insofar as the knowledge used in building models does not contain or refer to a specific notion of function or  $fm_{DS}$ , co-existence of models can be understood in terms of variation in knowledge usage. Yet, when the knowledge used does already refer to a specific notion of function or  $fm_{DS}$ , the choice for (the construction of) specific models is obvious, but explicating such choices in terms of knowledge employment would become circular. For instance, in the case of the objective of routine designing (characterized as the designing of new artifacts by using knowledge of

function-structure connections of existing types of the to-be-designed artifact) Deng (2002) puts forward purpose function  $fm_{DS}$  that are built using known connections between purpose functions and structures as means toward this objective. Since these connections are known and employed, purpose function  $fm_{DS}$  are obviously opted for. However, explicating the choice for these  $fm_{DS}$  in terms of the usage of known purpose function-structure connections would introduce circularity in the explanation. Moreover, as I will argue in the next section, effect function  $fm_{DS}$  and behavior function  $fm_{DS}$  that are also built using connections between these notions of function and structure, respectively, are advanced as well as means toward this objective of routine designing. Hence, different explanatory constructs than variety in objectives and variation in knowledge usage are needed to explain cases such as these. These constructs do not provide the requisite explanatory leverage when one wants to explain why different  $fm_{DS}$  are used side-by-side as means for achievement of the same objective, and the knowledge used to build them already refers to specific notions of function or  $fm_D$ . In such cases, other explanatory constructs are needed. The work of Kuhn and others on methodological incommensurability and the dynamics of theory choice provide concepts suited to explicate such cases, as I will argue in the next section.

#### 4. Methodological Incommensurability in Engineering

Kuhn (1970: 148-150) initially used the term incommensurability in a holistic fashion to capture methodological, observational, and conceptual incompatibilities between successive scientific paradigms. In later work (e.g. Kuhn 1991) he narrowed down and specified his notion of incommensurability further in terms of differences in the taxonomic structure of successive scientific theories. On this “semantic” reading of incommensurability, translation failure occurs between kind terms of competing theories due to the unmatchable classificatory schemes/taxonomic structures underlying these theories (Kuhn 1991). In such cases, theories classify the same objects into different kinds, the members of which are (taken to be) governed by different natural laws. Translation of kind terms between theories then will fail since the nomic expectations attached to these terms are incompatible between theories. For instance, Ptolemy’s theory classifies the sun as a planet, where planets orbit around the earth, whereas Copernicus’ theory classifies the sun as a star, where planets orbit stars. A Copernican claim such as planets orbiting the sun is incompatible with Ptolemy’s framework, hence translation of the kind term ‘sun’ between these theories will fail (Kuhn 1991: 94).

As Kuhn’s later treatment of incommensurability focused mainly on semantic aspects, some commentators began to distinguish two different notions of incommensurability: on the one hand the above-mentioned semantic incommensurability and on the other “methodological” incommensurability, which involves epistemic standards that are used to evaluate competing theories (Kuhn 1970, 1977; cf. Sankey 1999; Carrier 2008; Soler 2008; Oberheim and Hoyningen-Huene 2009).

##### 4.1. Methodological Incommensurability

The development of the thesis of methodological incommensurability is traced back to Kuhn’s (as well as Feyerabend’s) rejection of the view held by both the Logical Positivist movement and Popper that a distinguishing feature of science is the use of a uniform scientific method that remains fixed throughout scientific development, and on the basis of which theory choice can be determined unambiguously (Oberheim and Hoyningen-Huene 2009; cf. Kuhn 1970: 94, 103).<sup>7</sup> Kuhn challenged the view of an invariant scientific method that is capable of governing theory choice in such unambiguous fashion. He argued, instead, that standards or criteria of theory appraisal, such as accuracy, consistency, fruitfulness, scope, and simplicity (1977: 322) depend



on and vary between paradigms. Kuhn pressed the point that such standards do not function as algorithmic rules that are able to determine theory choice but rather as values that only guide it (1977: 331). Epistemic values refer to characteristics or properties of scientific theories that are considered desirable by scientists relative to their objectives. The history of science shows that disputes between advocates of rival theoretical frameworks are not solved by recourse to a neutral algorithm that is capable of dictating theory choice, since there is no commonly shared set of criteria or standards available on the basis of which such a choice can be forged (Kuhn 1970, 1977).<sup>8</sup> Based on this construal of theory choice in terms of values and the observation that scientists (can) differ in the values they employ, Kuhn (1977) concluded that scientists may rationally disagree in theory choice. This disagreement may have different sources. First, advocates of rival scientific frameworks may differ in the values they employ in theory choice and appraisal. Second, values may conflict when applied to concrete cases of theory choice. For instance, scope may favor one theory, yet simplicity another. Theory choice then entails assigning weight/relevance to such values, which advocates of rival frameworks may do so in different fashion. Third, advocates of rival scientific frameworks may also interpret the content of values differently. What is, for instance, precisely meant when one speaks about accuracy? Based on these considerations, Kuhn (1970, 1977) concluded that there is no commonly shared algorithm available for theory choice.

Summing up, key elements of this position are the closely related notions of “non-algorithmic theory choice” and “methodological variation” (Sankey 1995, 2002), that is, variation in how and/or which (set of) values are employed in theory choice. Furthermore, the theories in question are advanced to meet what we may call a ‘common objective’: they purport to explain the same (or substantially overlapping) range of phenomena (e.g. Soler: 2008). I use (and expand on) the notion of variation in values in section 4.2 to explain co-existence of different engineering  $fm_{DS}$  that are advanced as means to achieve a *common objective*.<sup>9</sup>

My earlier explanation of co-existence in terms of variation in knowledge usage (section 3.3) also hinges upon (though not phrased as such), in an engineering-modeling rather than a scientific-theoretical context, the idea of variation in values: knowledge usage specifics, such as employing known function-structure connections or behavior-structure relations during the construction of  $fm_{DS}$  correspond to values engineers have that influence their choices for particular models. These values are not ones that are operative in a scientific-theoretical context (epistemic values) but they do function similarly, in an engineering-modeling context, as factors that influence engineers their choices for particular  $fm_{DS}$ . Let us capture this similarity by calling such factors engineering-values, or “e-values” for short. I define an engineering value as a characteristic or property of a functional decomposition model or a functional decomposition strategy that is considered desirable by an engineer relative to an objective.<sup>10,11</sup> However, as indicated in section 3.3, e-values relating to knowledge usage do not provide the requisite explanatory leverage in the case of routine designing. I consider other e-values to explicate this case.

#### **4.2. Incommensurability in Engineering: the Case of Functional Decomposition and Routine Designing**

In the engineering literature, in the electro-mechanical domain, different  $fm_{DS}$  are advanced as means for achieving the (common) objective of “routine design”: behavior function  $fm_{DS}$  (Chakrabarti and Bligh 2001), effect function  $fm_{DS}$  (Kitamura and Mizoguchi 2003), as well as purpose function  $fm_{DS}$  (Deng et al. 2000a, 2000b; Deng 2002) are put forward as means for achieving this objective.<sup>12</sup> In the above accounts in which these particular models are advanced

this objective is characterized as the designing of new artifacts by using knowledge of function-structure connections of existing types of the to-be-designed artifact (references see above).

#### 4.2.1. Variation of e-Values

Analysis of these accounts shows that their developers advance different e-values that their proposed  $fm_D$ s are to satisfy. These e-values are given in Table 1.

|                                   |  |
|-----------------------------------|--|
| Structural compatibility          | The spatial organization that an $fm_D$ provides must be such that all functions of the structures contained in the spatial organization are achieved  |
| Function-behavior independency    | Descriptions of functions in an $fm_D$ should be such that they do not describe their underlying behavior and are organized in sets in terms of knowledge of their underlying behavior                                   |
| Function-to-function independency | The functions in an $fm_D$ must be independent from one another in the sense that realization of a given function by a structure is (considered to be) independent from realization of other function(s), and vice versa |

**Table 1:** e-values employed in  $fm_D$  choice

In the Chakrabarti-Bligh (CB) account  $fm_D$ s must satisfy the e-value of what we may call ‘structural compatibility’. The (input-output) organization of functions in an  $fm_D$  also provides a spatial organization of the structures that achieve them.<sup>13</sup> And the spatial organization that a model provides must be such that any negative interactions between structures (as a result of which structures would fail to achieve their functions) do not occur, so that all the functions of the structures contained in the spatial organization are achieved (Chakrabarti and Bligh 2001). In other words, structures contained in the spatial organization provided by an  $fm_D$  must be compatible with one another.<sup>14</sup>

In the Functional Concept Ontology (FCO) account (Kitamura and Mizoguchi 2003; Kitamura et al. 2005/6; Kitamura et al. 2007) another e-value, which we may call ‘function-behavior independency’ is emphasized. This e-value prescribes that descriptions of functions in  $fm_D$ s should be such that they do not describe their underlying behavior and are organized in sets in terms of knowledge of their underlying behavior (descriptions that do refer to underlying behavior are coined “quasi-functions”). These authors distinguish the concept of function from the concept of behavior. And in  $fm_D$ s those functions that make up another function are grouped together (organized) in sets based on knowledge of their underlying behavior and structure, thus distinguishing functional from behavioral descriptions.

Yet another e-value is emphasized in the Dual Stage (DS) account (Deng et al. 2000a, 2000b; Deng 2002), which we may call ‘function-to-function independency’. This e-value prescribes that the functions in an  $fm_D$  must be independent from one another in the sense that realization of a given function by a structure does not depend on the (prior) realization of another function by another structure (Deng 2002). For instance, a washing machine’s function of ‘washing laundry’ can be independent (for its realization) from its function of ‘drying laundry’ (Deng 2002). (In this account, the behaviors underlying the functions in an  $fm_D$  are not considered to be independent, but causally related).

As can be seen, different e-values for  $fm_{DS}$  hold in these accounts. This variation in e-values provides means to explain the choice for/construction of different  $fm_{DS}$  in these accounts, as I will argue below.

#### 4.2.2. Explaining $fm_D$ Choice by e-values

Given the emphasis in the CB account on the e-value of structural compatibility, one can understand why behavior functions  $fm_{DS}$  are (chosen to be) developed. When the spatial organization that an  $fm_D$  provides must be such that any negative interactions between structures (as a result of which structures would fail to realize their functions) do not occur, behavior function  $fm_{DS}$  are best equipped to provide such a spatial organization. Such  $fm_{DS}$  contain the details needed for assessing whether the output characteristics of one structure's function match/are compatible with the input characteristics of another structure's function. Say, the heat generated when energy is converted into torque by an electric screwdriver's motor may negatively interact with the electrical wiring connected to the motor, possibly leading to failure of their 'transmitting electricity' function (and hence the motor's function as well). Purpose and effect function  $fm_{DS}$  seem too course-grained to satisfy this e-value of structural compatibility. For instance, the effect function 'produce torque' of a screwdriver's motor does not contain the information required to assess its compatibility with the electrical wiring

In the FCO account, on the other hand, structural compatibility is already assumed to be in place. In these  $fm_{DS}$ , those functions that make up another function are grouped together (organized) in sets based on knowledge of their underlying behavior and structure (Kitamura et al. 2005/6). One needs to assume that the structures (and behaviors) underlying the functions in  $fm_{DS}$  are compatible for otherwise sets of functions making up/achieving other functions would fail to do so (these authors make this assumption:  $fm_{DS}$  are models of existing and working artifacts).

In the DS account, structural compatibility is not something that  $fm_{DS}$  should satisfy. Rather, in this account, both the assembly of structures and the verification of whether assembled structures meet the design requirements take place in later design phases after  $fm_{DS}$  are constructed (Deng 2002).<sup>15</sup>

Next to the structural compatibility assumption,  $fm_{DS}$  in the FCO account must satisfy the e-value of function-behavior independency. Given this e-value one can understand why effect function  $fm_{DS}$  are developed. When descriptions of functions in  $fm_{DS}$  must be such that they do not describe their underlying behavior and are organized in terms of their underlying behavior (and structure), behavior function  $fm_{DS}$  will (obviously) not be opted for since the functions in such models describe behaviors. And since functions in  $fm_{DS}$  are grouped together based on knowledge of their underlying behavior and structure one can also understand why purpose function  $fm_{DS}$  are not chosen. By using purpose function  $fm_{DS}$ , in which functions refer to states of affairs that are the final result(s) of behavior, one skips reference to the more immediate effects of behaviors and structures. Compared with effect function  $fm_{DS}$ , the grouping of functions in sets based on their underlying behavior and structure is less straightforwardly established with such purpose function  $fm_{DS}$ . In the latter case, the connection between function-behavior-structure is less straightforward. For instance, the purpose function "to tell time" can be achieved by a wide variety of behaviors and structures. The effect function description "rotate arms in clockwise direction" on the other hand is more easily connectable to specific behaviors and structures (and sets of such functions thus more straightforwardly organized in terms of behavioral and structural knowledge).

In the CB account, this function-behavior independency is not an e-value that  $fm_{DS}$  must satisfy. On the contrary, as we saw, in these  $fm_{DS}$  functions refer to behaviors. Neither do  $fm_{DS}$  satisfy this e-value in the DS account. Functions in purpose function  $fm_{DS}$  are not organized in terms of knowledge of their underlying behavior (what they do have in common with  $fm_{DS}$  in the FCO account is that functions in DS  $fm_{DS}$  do not describe their underlying behavior since they characterize states of affairs that are the final results of behaviors).

Given the third e-value of function-to-function independency that  $fm_{DS}$  in the DS account must satisfy, one can understand why purpose function  $fm_{DS}$  are developed. When functions in an  $fm_D$  are required to be independent from one another in the sense that realization of a given function is independent from the realization of other function(s), and vice versa, purpose function  $fm_{DS}$  seem most suited. Such models allow one to conceive most clearly of the realization of functions as being independent from the realization of other functions. For instance, realization of the behavior function ‘transmitting torque’ of an electric screwdriver requires, say, prior realization of the behavior function ‘converting electricity into torque’. Similarly, realization of the electric screwdriver’s effect function ‘produce torque’ requires, say, prior realization of the effect function ‘generate electricity’. In contrast, realization of the purpose function of, say, ‘having a rotational force’ is more easily conceived as independent from the realization of other functions. Hence, models of purpose functions satisfy this e-value best.

In contrast, function-to-function independency is not an e-value in the FCO account since functions in  $fm_{DS}$  that jointly achieve another function are grouped in sets (based on knowledge of their underlying behavior and structure) and hence not (considered to be) independently realized.  $Fm_{DS}$  in the CB account also do not satisfy this e-value. Functions in  $fm_{DS}$  are organized in terms of their input-output characterizations and thus for their realization dependent on one another (and on the structural compatibility of their underlying structures). This analysis is summarized graphically in Table 2.

|             | Structural compatibility | Function-behavior independency | Function-to-function independency |                          |
|-------------|--------------------------|--------------------------------|-----------------------------------|--------------------------|
| CB account  | +                        | -                              | -                                 | Behavior function $fm_D$ |
| FCO account | +                        | +                              | -                                 | Effect function $fm_D$   |
| DS account  | -                        | -                              | +                                 | Purpose function $fm_D$  |

**Table 2:** e-values and  $fm_D$  choice

#### 4.2.3. Co-existence and Methodological Incommensurability

Summing up, in these accounts different e-values are considered important, due to which different  $fm_{DS}$  are chosen for routine designing: behavior function  $fm_{DS}$  in the CB account, effect function  $fm_{DS}$  in the FCO account, and purpose function  $fm_{DS}$  in the DS account. And, in addition, some of these e-values conflict: function-to-function independency applies to DS purpose function  $fm_{DS}$  but not to CB behavior and FCO effect function  $fm_{DS}$ ; and function-behavior independency applies to FCO effect function  $fm_{DS}$  but not to DS purpose function and CB behavior function  $fm_{DS}$ . Of the three sources that each leads to methodological incommensurability (see section 4.1), two engineering variants can be identified in this case: (1) variation in and (2) conflict between e-values. Due to both this variety of and conflict between e-

values, there is in this case no commonly shared algorithm available that governs engineers' their choices of  $fm_{DS}$ . This choice, rather, is seen to be dependent on the e-values that engineers adopt. This divergence of e-values thus explains the co-existence of different  $fm_{DS}$  that are advanced as means to achieve a common objective. I submit that this functional decomposition case exemplifies an instance of methodological incommensurability in the engineering domain.<sup>16</sup>

In a similar vein as Kuhn (1970, 1977, 1983) explained scientists' choices for different theories in terms of differences in epistemic values, I thus offer an explanation why different  $fm_{DS}$  are used side-by-side in engineering in terms of variation in e-values. Kuhn's analysis of values, in addition, led him to conclude that scientists' choice of (competing) theories can be considered rational. This conclusion has spawned extensive debate in philosophy of science (Kuhn 1977; McMullin 1983; Laudan 1987; Worrall 1988; Sankey 1995, 2002). Initially, a key issue was whether in the absence of a commonly shared algorithm scientists' choice of theories can in fact be considered rational. More recently, this debate has shifted in orientation: both advocates of a single method for theory choice and authors that accept variation in values are pressed to show that their preferred single method or spectrum of values ensure the rationality of scientists' choice of theories (Worrall 1988; Sankey 1995, 2002).

I will address this issue in the engineering functional decomposition case: can engineers' choices for different  $fm_{DS}$  be considered rational from an instrumental point of view? I will argue that variation in e-values ensures that the choice and usage of different  $fm_{DS}$  by different engineers is rational from a practical point of view.

## 5. Rationality in Engineering

### 5.1. Values and Theoretical Rationality

Kuhn (1983) took the position that the rationality of scientists' choice of theories is ensured by the concept of science itself (see also Sankey 1999). Kuhn's position has however been criticized on the grounds that he never satisfactorily addressed the challenge to explicate how variation in epistemic values ensures rational theory choice (Hempel 1983; Sankey 1999). In the case of values, the challenge is to show that the values one considers are appropriate ones for the evaluation and choice of scientific theories. A value is considered appropriate for theory choice if a theory that satisfies a particular value contributes to the attainment of a scientific objective (that one aims to achieve with the theory) precisely because the theory satisfies that value (Hempel 1983; McMullin 1983; Sankey 2002). Stated differently, that the (desired) characteristics or properties of the chosen theory indeed are the features by means of which the theory contributes to attainment of an objective that one aims to achieve with the theory. Insofar as values are appropriate, maintaining variation of these values in theory choice is considered rational. Advocates of value variation consider such means-end interpretations of values an asset (Laudan 1987; Teller 2008). It allows for the possibility to rationally compare the merits of competing theories (or scientific models): this theory/model is better with respect to this value, that theory/model is better with respect to that value.

Several interpretations of such means-end relationships between epistemic values and scientific objectives are given in philosophy of science. Some assert that appropriate values contribute to the attainment of a main or ultimate objective of science, such as empirical adequacy or truth (McMullin 1983). Others do not invoke the notion of an ultimate objective and argue that specific values contribute to more specific objectives (Laudan 1987; Teller 2008). Sankey (2002) gives a third interpretation by combining the two interpretations above. Sankey views these more specific objectives as subordinate to a main or ultimate objective of science, which in his book is

advancement on the truth. He takes the achievement of subordinate objectives as sub serving this main or ultimate objective of science. In Sankey's scheme on thus finds epistemic values, their related subordinate objectives, and a common ultimate objective

Based on this means-end interpretation of epistemic values, Sankey (2002) defends methodological variation: insofar as values are conducive to the realization of their related subordinate objectives, maintaining variation of these values in theory choice is rational.<sup>17</sup>

I use and expand on Sankey's means-end analysis of epistemic values, specifically his distinction between subordinate objectives and a main objective, to show that the e-values that I consider are appropriate ones for the evaluation and choice of  $fm_{DS}$ . In the engineering case I speak of sub objectives rather than subordinate ones. As I will argue in the next section, this analysis indicates that engineers' choices for different  $fm_{DS}$  are rational from an instrumental point of view.

## 5.2. e-Values and Practical Rationality

I will demonstrate in the following that an  $fm_D$  that satisfies a particular e-value contributes to the attainment of the objective for which the  $fm_D$  is used precisely because it satisfies that e-value, i.e., that the (desired) characteristics or properties of the chosen  $fm_D$  indeed are (among) the features by means of which the model contributes to attainment of the objective for which it is used. To demonstrate that  $fm_{DS}$  satisfying the e-values that I consider are suitable means to achieve the objectives for which they are used, I distinguish between main and sub objectives of engineers. I argue that different  $fm_{DS}$ , precisely because they satisfy particular e-values, directly contribute to the attainment of particular sub objectives and indirectly, via the achievement of sub objectives, to main objectives. This analysis in terms of sub objectives makes it insightful how different  $fm_{DS}$  that satisfy different (and conflicting) e-values all contribute to a common main objective. This analysis thus also indicates that specific models have specific advantages: depending on the e-values and sub objectives that engineers have, specific  $fm_{DS}$  are better than others. By implication, my analysis shows that the usage of different  $fm_{DS}$  by different engineers is rational from a practical point of view.

Returning to the first e-value of structural compatibility that is satisfied by  $fm_{DS}$  in the CB account, we can explicate these  $fm_{DS}$  as contributing to a sub objective of what we may call "accuracy", to wit: that all the functions in an  $fm_D$  are realized. In order for this sub objective to be achieved an  $fm_D$  must satisfy structural compatibility: the spatial organization that an  $fm_D$  provides must be such that any negative interactions between structures do not occur, so that all the functions of the structures contained in the spatial organization are realized.<sup>18</sup> Since this e-value is already assumed to be satisfied in the FCO account, so is its related sub objective. In the DS account, this e-value and sub objective are addressed in later design stages after  $fm_{DS}$  are constructed.

In similar fashion we can interpret  $fm_{DS}$  satisfying the e-value of function-behavior independency, as endorsed in the FCO account, as contributing to a sub objective of what we may call "knowledge management of design rationale". This account aims to capture (rather ambitiously) the rationale of engineers that lies behind their construction of particular functional descriptions and  $fm_{DS}$  (for archival and cross-communication purposes in design) (Sasajima et al. 1996; Kitamura et al. 2007). Capturing such "design rationale" is according to these authors in engineering done in an idiosyncratic fashion in the sense that its analysis depends on the considerations of the model builder. They aim to overcome this idiosyncrasy by developing systematic guidelines for the capturing of design rationale behind  $fm_{DS}$  in more explicit and reusable fashion. Key assumption in the development of these guidelines is that of all the possible

input-output relations of technical behaviors only some input, output, or input-output relations are intended in a given context and hence will be used for developing functional descriptions and  $fm_{DS}$ . They also define primitives to isolate those input, output, or input-output relations that are used to develop descriptions of functions and  $fm_{DS}$  in particular contexts (Sasajima et al. 1996). Given this aim to capture design intent systematically, that is, the sub objective of “knowledge management of design rationale”, and this key assumption underlying it, we can interpret  $fm_{DS}$  satisfying the e-value of function-behavior independency as contributing to this sub objective. Given this underlying assumption,  $fm_{DS}$  satisfying the e-value of distinguishing function from its underlying behavior contribute to capturing design intent in systematic fashion. This e-value and sub objective are not emphasized in the CB and DS accounts.

$Fm_{DS}$  satisfying the e-value of function-to-function independency, as endorsed in the DS account, can be analyzed as contributing to a sub objective that we may call “broad scope in function-structure mapping”. If functions-structure connections can be considered independent from other function-structure connections, one can search the available spectrum of design solutions to a given function. If the realization of a function by a structure would depend on the (prior) realization of another function by another structure, the range of structure-function connections would decrease. A selection of a particular design solution to a function would then constrain the possible design solutions one can choose for functions that must be realized prior to this function. By considering function-structure connections as independent, this constraint does not apply. Hence, a broad range of functions-structure connections can be considered

Achievement of each of these sub objectives, in turn, all contributes to the main (and common) objective of routine designing. The sub objective of accuracy that all the functions in an  $fm_D$  are realized is crucial to the design of any artifact, irrespective of whether it is arrived at in routine or innovative fashion. Achievement of the sub objective of establishing knowledge management of design rationale – facilitating the consistent archival and cross-communication of design knowledge – is clearly instrumental toward the designing of artifacts in collaborative settings. And achievement of the sub objective of having broad scope in function-structure mapping, i.e., keeping the range of potential structures for functions as broad as possible, may support ‘innovative/creative’ combinations of structures of an artifact-to-be.

We thus reach the conclusion that the e-values that I considered are appropriate ones for the evaluation and choice of  $fm_{DS}$ : particular  $fm_{DS}$  are suited to achieve particular sub and main objectives because these  $fm_{DS}$  satisfy particular e-values. This analysis in terms of e-values shows that specific models have specific advantages: depending on the e-values (and sub objectives) that engineers deem important, specific  $fm_{DS}$  are better than others. For instance, if one values compatibility of structures, then one better opts for a behavior function  $fm_D$ ; if one values independence of function-structure connections, one better picks a purpose function  $fm_D$ . There is not one  $fm_D$  that satisfies all such engineering values best. Hence, I submit that the usage of different  $fm_{DS}$  by different engineers is rational from a practical point of view.

A qualification is in order. From the analyzed case it does not automatically follow that functional modeling research will not eventually converge toward a single  $fm_D$ . What the analysis does show is that modeling researchers have valid reasons not to do so, and my bet is that they will not. Another issue is whether the modeling field will eventually settle on a best behavior function  $fm_D$ , effect function  $fm_D$ , and purpose function  $fm_D$ , respectively. Given the current plethora of functional modeling accounts, it may turn out at some point in the future that the current situation is then interpreted as, say, “pre-paradigmatic”, and accounts will have converged toward, say, three best accounts for the modeling of behavior function  $fm_{DS}$ , effect function  $fm_{DS}$ , and purpose function  $fm_{DS}$ , respectively. My bet is that this scenario is unlikely as well: closer scrutiny will

probably reveal other e-values and sub objectives that are served especially well with particular variants of the three considered  $fm_{DS}$ . For instance, effect function  $fm_{DS}$  in which the functions are represented by triggers and effects (see the "switch on-light on" example in section 3.3) seem better suited for failure analysis than effect function  $fm_{DS}$  in which functions are represented in term of desired output only (e.g. "light on").

## 6. Conclusion

In this paper I have explained the co-existence of different models of functional decomposition in terms of the thesis of methodological incommensurability. I advanced this analysis in terms of the thesis' construal of (non-algorithmic) theory choice in terms of values, expanding this notion to the engineering domain. I further argued that co-existence of different models of functional decomposition is rational from an instrumental point of view.

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## Endnotes

1. For instance, the efforts spend in psychiatry and clinical psychology to arrive at unambiguous and shared classification criteria for psychiatric disorders as laid down in the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV) (see American Psychiatric Association: 2000).
2. I use the term "Kuhnian" since the thesis is labeled by some of Kuhn's commentators as methodological incommensurability but not so by Kuhn himself. Whereas Kuhn's earlier (1970) incommensurability thesis

contains both methodological and semantic aspects, he focused in later work more exclusively on semantic notions such as translation-failure and taxonomic structure (e.g. 1991). Due to this more specific focus, some commentators began to distinguish semantic incommensurability from methodological incommensurability (e.g. Sankey 1999). Kuhn's most explicit treatments of methodological incommensurability can be found in (Kuhn 1977, 1983). The thesis is currently more frequently discussed under such headings as 'rationality of theory choice' and 'epistemological relativism' (Sankey 1999).

3. The distinction between effect and purpose function is not completely clear-cut: both relate to features of behavior. Yet, purpose function descriptions, such as 'having a rotational force down a shaft', are, typically, phrased in terms of a result of behavior in the environment of a technical artifact. Effect function descriptions, such as 'producing torque', are phrased in terms of behavioral features of a technical artifact (this distinction originates from Chandrasekaran and Josephson (2000) who distinguish between device-centric and environment-centric descriptions of functions). Behavior functions can be distinguished clearly from effect and purpose functions: in behavior function descriptions physical conservation laws are taken into account, whereas this is not the case in effect and purpose function descriptions. For instance, in the description 'producing torque', the conservation of energy is not taken into account. In 'converting electricity into torque and heat' the input energy of electricity is supposed to equal the output energies of torque and heat, thus taking physical law into account.
4. In (Van Eck 2009, 2011) I analyze a number of accounts in terms of the notions of function and models of functional decomposition that they advance.
5. These devices are a part of automatic assembly systems for manufacturing electronic connectors. They are used to insert terminals into a housing in order to make a conductor and an insulator one unit (cf. Deng 2002)
6. To avoid misunderstanding, I am not pressing the claim that an objective fixes a specific knowledge usage, which in turn fixes what counts as the most adequate model. An objective then would fix the most adequate model. I am, rather, advancing the claim that (the choice for) a specific knowledge usage impacts the suitability of a model. The choice to employ specific knowledge may differ between modeling accounts, whereas the objective they target is the same. For instance, one may envision the design strategy to use known function-structure connections for building models in innovative design under the assumption that it reveals when such knowledge is insufficient to take care of all required functionalities, indicating that new knowledge on (novel) function-structure connections is required (Chakrabarti and Bligh 2001). This differs from the design strategy of Stone and Wood (2000) in which knowledge of function-structure connections is explicitly not employed during the construction of models, but only after models are built. Both these choices with respect to knowledge use seem sensible ones for achievement of the objective of innovative design. So, knowledge usage in the construction of models is the crucial parameter in my analysis to explicate the choice for and co-existence of models.
7. See Worrall (1988) for a more recent defense of a fixed scientific method.
8. Rival in the sense that these theories purport to explain the same or (overlapping) range of phenomena (e.g. Soler: 2008). Otherwise, incommensurability issues do not arise of course.
9. Semantic incommensurability does not provide the relevant footing for explicating co-existence: translations between different  $fm_{DS}$  are, after doing some conceptual groundwork, possible. Behavior function  $fm_{DS}$  can, for instance, be translated into physical behavior models after which the relevant information can be extracted from these behavior models to construct effect function  $fm_{DS}$  (Van Eck 2009/2010, 2010c).
10. Applying the notion of variation in values to engineering rather than science is unproblematic. Values are not specific to science (e.g. McMullin: 1983). In different contexts, in casu science and engineering, values convey the (same) idea that a characteristic or property of an item or entity is considered desirable. The more discriminative notions of epistemic value and engineering value, of course, are specific to these contexts and relate to different items: epistemic values relate to scientific theories, and engineering values relate to  $fm_{DS}$  or strategies.
11. E-values relating to knowledge use refer to the process of building  $fm_{DS}$ , i.e., to functional decomposition strategies. The e-values that I consider in the next section refer to features of  $fm_{DS}$ . One can rephrase this process feature as a model feature. For instance, not employing known function-structure connections in model building can be rephrased as, say, 'function-structure independency'. In the engineering literature, the term "form-independent" (Stone and Wood 2000: 359) is often employed.
12. In (Van Eck 2009) I spell out the claim that these  $fm_{DS}$  are put forward in these accounts.

13. I borrow the term spatial organization from the mechanistic explanations-literature (e.g. Machamer et al. 2000).
14.  $fm_{DS}$  are the end result or product of a series of design reasoning steps. They are constructed in step-by-step fashion by first selecting (from a knowledge base) a function and an associated structure, then it is assessed which functionality is solved and which still remains to be solved, then another function and associated structure (that is compatible with the first selected structure) are selected, then again an assessment is made of the solved and still unsolved functionalities, after which again a function and structure are selected (compatible with the already selected structures) etcetera, until these selected functions jointly achieve an overall function/achieve all required functionalities (due to the spatial organization of their associated structures). The end result of this process is an  $fm_D$  that satisfies the structural compatibility e-value.
15. To be sure, the constraint that all structures are compatible with one another (and, hence, all functions realized) is of course a crucial constraint that is valued in all functional modeling frameworks. Modeling frameworks differ, however, in which design phase this value is to be satisfied. In some accounts  $fm_{DS}$  should satisfy this value (Chakrabarti and Bligh 2001), whereas in others it should be satisfied in later design phases (Deng et al. 2000; Deng 2002). Thus, only in some accounts is it a value that applies to  $fm_{DS}$ .
16. Perhaps someone might object to this latter conclusion/existence proof on the grounds that the term incommensurability should be reserved to a scientific-theoretical context, period. I disagree but if this causes too much cognitive dissonance, let us not skirmish over words. My purpose in this paper is to understand co-existence of distinct  $fm_{DS}$  for the same objective and (expansion into engineering of) the thesis of methodological incommensurability allows me to do so.
17. Hoyningen-Huene (1992) endorses a similar position, arguing that values are “something like execution procedures” (498) for the ultimate goal of science “to produce general, explanatory theories about the world” (499), and that they “concretize this goal in an operationally meaningful way” (499).
18. Chakrabarti indicated – personal communication on August 26, 2009, Stanford, CA, USA – that the account he developed with Bligh is explicitly geared toward satisfying these, what I labeled, e-value and sub objective by means of the steps described in note 14. The assumption that they are already satisfied when using knowledge of existing artifacts in routine designing is in his view often negated by actual design cases.