Artificial Intelligence for Engineering Design, Analysis and Manufacturing (2013), *27*, 241–248.

doi:10.1017/S0890060413000243

RESPONSE PAPER

Toward a scientific ontology based concept of function

YONG CHEN, ZHINAN ZHANG, JIAN HUANG, AND YOUBAI XIE

School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai, China

(RECEIVED March 1, 2012; ACCEPTED March 1, 2013)

Abstract

Function is an ambiguous concept, whereas having explicit and precise concepts is critical for building a systematic science of engineering design. Based on Bunge's scientific ontology, this paper is devoted to developing an explicit and precise concept of function for design science. First, we attempt to clarify the concept of behavior, which is closely related to function and is also shown as an ambiguous concept in engineering. Second, the concept of action is imported from scientific ontology into design science. Third, a scientific ontology based concept of function is proposed, together with an ontology-based functional taxonomy. A case of a function definition of a civil aircraft type demonstrates that the proposed concept of function is more explicit and precise than previous ones, and it can lead to better functional design results.

Keywords: Action; Behavior; Design Science; Function; Scientific Ontology

1. INTRODUCTION

In design science, function is usually regarded as a critical concept in research on design theory and methodology (e.g., Hubka & Eder, 1996; Pahl & Beitz, 1996; Suh, 2001). In industry, function is regarded as a key concept in some engineering design guidelines (e.g., VDI 2221, Verein Deutscher Ingenieure, 1993; ARP-4754A, SAE Aerospace, 2010). It seems that there is in design science already an explicit and precise concept of function. However, function has been defined in multiple different ways and is currently an ambiguous concept, as pointed out in recent reviews (Erden et al., 2008; Vermaas, 2013). Typical understandings are, for example, *function as input–output transformation* (Pahl & Beitz, 1996), *function as purpose* (Gero & Kannengiesser, 2004), and *function as intended behaviors* (Goel et al., 2009). As pointed out by Vermaas (2013), design methodologists have been aware of the coexistence of such different meanings for more than a decade, but they usually avoid disputes or other efforts aimed at resolving it.

A direct consequence of the ambiguity of the concept of function is that different functional descriptions can be given to one and the same artifact, even if it is used in the same situation. For example, multiple functions can be given to a hair dryer, such as *to blow and heat air*, *to dry (wet) hair*, or *to evaporate water (on hair)*. This consequence is probably harmless, given that many designers largely depend on past experiences when incrementally developing some technical artifacts, as is the case for building tools design companies (Eckert, 2013). However, it may become rather serious when designing some complex artifacts (e.g., civil aircrafts) through systematic design processes, which often entails an initial function definition task. Without an explicit and precise concept of function, it would be impossible for designers to develop an explicit functional model (Eckert, 2013), thus hampering the implementation of such systematic design processes.

Although function will remain in the near future as an ambiguous concept in engineering, the authors believe that a single concept of function will eventually emerge in design science, because such a concept is not only necessary for developing a systematic science of engineering design but also indispensable for applying design science to industry. Note that this concept of function need not fit all engineering fields (such as design, analysis, and diagnosis), because the meanings of function usually depend on different kinds of engineering tasks or different methodological goals (Goel, 2013; Vermaas, 2013). In our opinion, an ideal concept of function for design science should possess three basic features. First, it should have an explicit philosophical foundation, and thus it will not easily raise contradictions. Second, it should be described with terms that have been developed in science. Third, it should be able to bridge the gap between the human need domain and the physical solution domain, as

Reprint requests to: Yong Chen, Room 838, School of Mechanical Engineering, Shanghai Jiao Tong University, No. 800, Dongchuan Road, Minhang District, Shanghai, 200240, China. E-mail: mechenyong@sjtu.edu.cn

required by most systematic approaches to engineering design (e.g., Pahl & Beiz, 1996; Suh, 2001).

It has been widely accepted that ontology can help engineers and scientists to reach explicit and sharable concepts and knowledge about the world (e.g., Guarino, 1995). Therefore, this paper attempts to employ Bunge's (1977) scientific ontology to build a function concept for design science. The reasons why scientific ontology is adopted here are that, on the one hand, it is a widely accepted ontology in scientific philosophy and, on the other hand, it has dealt with several explicit concepts (e.g., behavior) that are closely related to the concept of function. This paper can be taken as adopting the revisionary approach to functional descriptions in engineering (Vermaas, 2013) through proposing a single concept of function for design science. It will present definitions of function and other related concepts, it will also give some detailed commitments of such concepts, and it will compare the proposed concept of function with existing understandings.

This paper is organized as follows. With the aid of scientific ontology, Section 2 attempts to clarify the concept of behavior for design science. Section 3 introduces the concept of (physical) action in scientific ontology, which is helpful for understanding the concept of function. A scientific ontology based concept of function is then developed in Section 4, followed by a case study in Section 5. Finally, Section 6 concludes this paper.

2. BEHAVIOR

Many engineering design studies have related function with behavior, and some of them even employ behavior to define function. However, just like function, behavior is also an ambiguous concept in engineering design. Therefore, it is indispensable to clarify the behavior concept first. Note that we are primarily concerned with physical behavior here.

2.1. Behavior in scientific ontology

Bunge's scientific ontology does not give a direct definition for behavior. It only deals with the word *behavior* in some sentences. A representative sentence is as follows: "Clearly if one of the things acts upon the other, then while the *behavior* line of the agent remains unaffected, that of the patient becomes, . . ." (Bunge, 1977, p. 257). Here, the behavior line refers to the state (change) line of a thing (i.e., the trajectory of a state or its change) over a period of time.

Therefore, based on scientific ontology, it is reasonable to define *the behavior of a thing as its state or state change over a period of time*. Here, a thing refers to a physical entity (i.e., a substantial individual) endowed with all its properties (Bunge, 1977). For example, when we say, "a car is moving from city A to city B," what is described is the "moving" behavior of the car, while "from city A to city B" is an adverbial phrase for modifying its behavior state change over time. To have an explicit concept of behavior, some ontological commitments about behavior are given below.

First, any behavior belongs to a thing, which accords well with Bunge's viewpoint (i.e., any state or state change belongs to a thing). Note that the thing that a behavior belongs to can also be regarded as its subject (Chen et al., 2011). For example, in the behavioral description mentioned above, the moving behavior belongs to the car, which can also be regarded as the behavior's subject.

Second, a behavior can be directly associated with a physical state variable, which is self-evident in scientific ontology. For example, the moving behavior mentioned before is actually related to the state variable *location*, which is not explicitly pointed out though.

Third, behaviors can be classified as static behaviors and dynamic behaviors (Chen et al., 2011). A dynamic behavior refers to the state change of a thing (e.g., the car's moving behavior mentioned before). In contrast, a static behavior deals with the invariable state of a thing over a period of time. For example, in the description *a paperweight is standing on a pile of paper*, the standing behavior of the paperweight is a static behavior.

Fourth, because a behavior describes the state (change) of a thing itself, it should be described with an intransitive verb (Chen et al., 2011). For example, the verb *stand* or *move*, in the aforementioned behavioral descriptions, is either an intransitive one or used in an intransitive way.

Fifth, according to scientific ontology, behaviors can be further classified as induced behaviors and spontaneous behaviors. An induced behavior refers to the passive state change of a thing directly caused by the external action of another thing. For example, in the description "a table moves as a man pushes it," the table's moving behavior is an induced behavior. In contrast, a spontaneous behavior is totally active (e.g., the rotating behavior of the Earth).

It is expected that the ontological commitments listed above can help designers form a scientific ontology based concept of behavior and can provide some guidelines about how to describe a behavior. In addition, they can also serve as some criteria for judging whether a description is a behavioral one.

2.2. Comparisons

Based on the ontological concept of behavior mentioned above, it is now possible to analyze the existing definitions of behavior in engineering to see whether they accord with the proposed ontological meaning of behavior. Due to limited space, only two representative definitions are employed for comparisons.

One representative definition is given by Bobrow (1984) in artificial intelligence research, by which a behavior refers to the time course of observable changes of state of the components and the system as a whole. By this definition, the behavior of a component or a system can be regarded as its own state change in a time course. It is, therefore, basically consistent with the ontological definition of behavior mentioned above, except that it does not take static behavior into consideration.

The second definition is given by Gero and Kannengiesser (2004), who argue that behavior refers to what an object does. For example, the behaviors of a window (i.e., what a window

https://doi.org/10.1017/S0890060413000243 Published online by Cambridge University Press

does) include light transmission, ventilation restriction, winter solar collection, and so forth. Such an understanding of behavior is also shared by some other researchers in engineering design, as reviewed in our recent research (Chen et al., 2011). However, this behavior concept is not an ontological one and can lead to philosophical issues (i.e., the behavior of an entity may unreasonably depend on properties that do not count as properties of the entity), which have been pointed out by Dorst and Vermaas (2005). For example, because airflow cannot be treated as an ontological property of a window, it is then not so reasonable to treat ventilation restriction (i.e., airflow restriction) as an ontological behavior of the window. It is more suitable to treat such behaviors (e.g., ventilation restriction) as actions, another concept to be introduced in Section 3.

Compared with the definition given by Gero and Kannengiesser (2004), the scientific ontology based concept of behavior will not incur the aforementioned philosophical issue and is therefore more explicit. According to scientific ontology, the behaviors of a window are, for example, *to rotate for a wider open angle* or *to shrink into a smaller size in a cold weather*, but this concept will not deal with the processes such as airflow restriction.

3. ACTION

In contrast with the concept of behavior, little engineering design research has formally dealt with the concept of action. However, this concept is also closely related to the concept of function (Chen et al., 2011). Therefore, we continue with introducing the concept of action. Note that what is of primary concern here is physical action, although the concept of mental action will also be discussed. If not pointed out otherwise, the word *action* will refer in this paper to physical action.

3.1. Action

Actions (i.e., physical actions) are ubiquitous in the physical world. Scientific ontology gives a formal definition for physical action (Bunge, 1977, p. 258).

> Let x and y be two different things with state functions F and G, respectively, relative to a common reference frame, and let $h(x)$ and $h(y)$ be their respective state histories. Let H be a third state function, depending on both F and G, and call $h(y|x)$ the corresponding (state) history. Then x acts on y, if for some state function H determining the state trajectory $h(y|x)$, $h(y|x) \neq h(y)$.

In this definition, the state function refers to a mathematical function regarding the trajectory of a state change over a period of time; the common reference frame can be regarded as a common reference coordinate, with its vertical axis and its horizontal axis representing the state variable of interest and the time variable, respectively; a state history denotes a state trajectory. Some significant ontological commitments of the concept of action are as follows.

First, according to scientific ontology, an action must deal with two things. If analyzed from the perspective of the subject–object relation, the thing (x) that exerts the action can be treated as subject, and the thing (y) that is acted upon can be treated as object (Chen et al., 2011). For example, in the action *an oven is heating food*, the oven is the subject and the food is the object. In contrast, a behavior only deals with one thing, which can be regarded as the subject of the behavior.

Second, what an action primarily concerns is the result (i.e., state change) of the action on the object, that is, $h(y|x)$, which means that an action emphasizes a state change of the object (Chen et al., 2011). For example, in the oven case mentioned above, what is emphasized is that the food (i.e., the object) gets heated (i.e., its temperature goes up). In contrast, a behavior is concerned with the state or state change of a subject.

Third, because an action requires a common reference frame in scientific ontology, the state function of the subject, that is, $h(x)$, should share the same state variable (h) as that of the object, that is, $h(y)$. This is an important commitment for differentiating an action from its indirect influence(s). For example, if a hot thing x is put together with a cool thing y, a heating action will make y heated, where the common state variable is temperature. If the thing y still has good heat extensibility, an indirect state change will also occur, that is, the size of y extends. If the common state variable were not required, it would be difficult to tell which state change (i.e., the temperature increase or the size extension) is the direct result of the heating action.

Fourth, an action usually should be described with a transitive verb to show the action of its subject upon the object (Chen et al., 2011). For example, in the aforementioned action description, *an oven is heating food*, the verb *heat* is used in a transitive way. This is completely different from a behavioral description, which should employ an intransitive verb.

Fifth, an action must correspond to a physical law, which prescribes the action manner between the subject and the object (Chen et al., 2011). In an ideal action description, the action manner should be declared to avoid ambiguity. For example, the aforementioned action should be ideally described as *a stove heats the room air via heat-exchange*, where *heat-exchange* is a specific action manner (rather than other action manners, e.g., *heat-radiation*). In contrast, a behavior merely deals with what state change happens to a thing, other than how it is changed.

It is expected that the ontological commitments mentioned above can help designers form an explicit concept of action and can guide them about how to explicitly describe an action. Based on such commitments, it can be found that the behavior concept is fundamentally different from the action concept.

3.2. Mental action

Besides (physical) actions introduced in scientific ontology, there are also mental actions that exist in the mental world. A mental action can be regarded as the conceptualization of a *physical process* in the human mind (Chen et al., 2011). Note that the *physical process* here can either be a physical

https://doi.org/10.1017/S0890060413000243 Published online by Cambridge University Press

action, a physical behavior, or even their combinations. A typical mental action is that a refrigerator stores fresh food. Here, the physical process is primarily composed of the physical action, *the refrigerator cools the germs on the fresh food*; the physical behavior, *the reproduction speed of the germs slows down as they get cooled*; and therefore the physical action, *the decay action of the germs on the food slows down*. Mental actions and physical actions share some similar features. For example, a mental action also has a subject and an object; a mental action should also be described with a transitive verb.

Mental actions can be classified as subjective actions and objective actions (Chen et al., 2011). A subjective mental action is a subjective conceptualization of a physical process, which is imaginary and does not directly correspond to a physical action. In contrast, an objective mental action is an objective and correct conceptualization of a physical action in human minds. Furthermore, there exists a one-to-one corresponding relationship between an objective action and a physical action. Because a design process often takes place in the mind of designers, what are actually involved in designing are objective mental actions, which can be regarded as the surrogates in designers' mind of physical actions.

In engineering design practices, an interesting phenomenon is that many subjective actions are often unconsciously misunderstood as objective (i.e., physical) actions. For example, some designers probably think that a hair dryer has an objective action on hair (i.e., drying hair) that is actually a subjective action. This is because when the hair-drying action is mentioned, it actually implies a subjective conceptualization of the hair, that is, the hair has two subjective states (i.e., dry and wet), where the physical entity of interest is merely regarded as hair. However, if investigated from a physical perspective, it could be found that the physical action behind the hair-drying process is that the water on hair is heated for speeding up its evaporation process, where the directly related physical entity is actually water (other than hair). Therefore, the hair-drying action should be regarded as a subjective action, rather than an objective action.

4. FUNCTION

As mentioned before, function should bridge the gap between the human need domain and the physical solution domain in design science. Because human needs (e.g., amusing) are often subjective, while physical solutions are objective, function therefore should be an intermediate concept that possesses both subjective attributes and objective ones.

4.1. A scientific ontology based concept of function

Engineering design activities exist because the physical worlds around human beings are in undesirable states or can possibly change into undesirable states. Therefore, *the function of an existing/desired physical system can be regarded as a special kind of desired mental action on the objective world of interest, which is expected to change the objective world from a problematic state into a satisfactory one or to prevent it from changing into an undesirable state*. Hereby, the desired special kind of mental action can also be called *functional action*, while the objective world refers to an objective conceptualization of the physical world (i.e., the surrogate of the physical world in the mental world). Note that the function concept here must deal with physical (i.e., objective) entities and therefore are not suitable for energy- or signal-focused functions.

Functional action also shares some similar points with physical action. For example, a functional action also has a subject and an object, and it should also be described with a transitive verb. Some significant commitments of functional action are given below.

First, because a functional action should be related to an objective (i.e., physical) world, it should be described in terms of physical state variables. This commitment is critical for differentiating functional actions from purely subjective actions, which cannot be described with tangible physical states. For example, the function of a hair dryer should be described as to separate water from hair, which, based on our previous research (Chen et al., 2007), can be represented as a location relation transformation, that is, $(HAIR.Location = WATER.Location) \rightarrow (HAIR.Location \neq WATER.Location)$, rather than as to dry hair, which could be subjectively conceptualized as a transformation with a nonphysical state, for example, $(HAIR.Dry\_State = false) \rightarrow (HAIR.Dry\_State = true)$, where *Dry_State* is a nonphysical state variable.

Second, different from a simple physical (i.e., objective) action, a functional action not only can be a generalization of multiple physical actions used in a system, but also can be achieved with some spontaneous behaviors, or even a combination of both physical actions and behaviors. For example, when a hair dryer is employed to separate water from hair, the primary physical action is that the hot airflow output by the hair dryer heats the hair, while the drying process also involves a significant physical behavior, *water evaporates into gas*, a spontaneous behavior that can accelerate as the temperature of the water goes up.

Third, the consequence of a functional action must correspond to the directly intended world state to be achieved for the physical world of interest. Such a commitment is important for differentiating the function of a system from its objective (i.e., physical) actions and is also crucial to keep a functional description conforming to a human need. For example, without this commitment, one could say that the function of a hair dryer is to heat the water (on hair). However, because the temperature increase of water is not directly intended, treating the physical action of heating water as the function of a hair dryer does not accord with the human need.

Fourth, unlike a physical action that merely deals with the physical state change of one thing (i.e., one object), a functional action deals with the state change of a world, which may comprise multiple things as objects and thus is more complex. For example, in the function of separating water from hair, there are two things as objects (i.e., water and hair), and what it is actually concerned with is not the specific state change of either thing but the location relation between the two things (i.e., they should not be in the same location; as shown before).

Fifth, a functional action should be represented in a way independent of any specific physical processes for achieving it (Chen et al., 2011). This commitment is consistent with the requirement from Pahl and Beitz (1996), that is, that function should be represented in a solution-neutral way to enable the generation of promising principle solutions in a wide solution space.

Based on these commitments, it can be found that the scientific ontology based concept of functional action is different from the concepts of objective (i.e., physical) action and subjective action. The relationship between functional action and the aforementioned concepts can be illustrated with the set-based graph shown in Figure 1. Note that the subjective action set is not directly indicated in the figure, because it is equivalent to the set difference of the mental action set and the objective action set. From this figure, it can be found that our concept of functional action is an intermediate concept between the objective world and the subjective world. This figure can also explain how known physical actions and known physical behaviors are conceptualized as different mental objects. For example, a physical action (a_p) can be conceptualized as an objective action (a_o); a physical behavior (b_p) can be conceptualized either as an objective behavior (b_o) or even as a functional action (a_f).

4.2. An ontology-based functional taxonomy

Based on the general functional taxonomy (Chen et al., 2007), an ontology-based functional taxonomy can then be

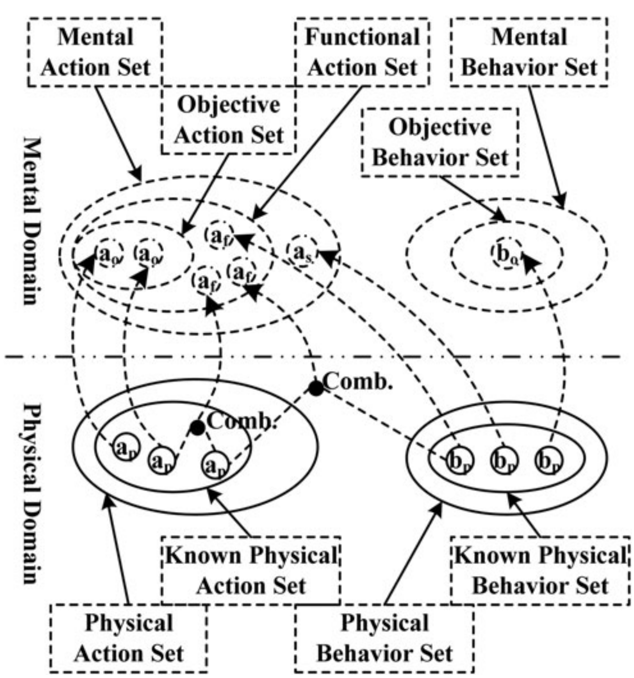

Fig. 1. The relations among various concepts.

developed. Because a physical world often deals with the static state of a thing, the dynamic behavior of a thing, the action of one thing on another, and the relations between two or more things, functions can then be ontologically classified as state-focused functions, (dynamic) behavior-focused functions, action-focused functions, and relation-focused functions.

A state-focused function means that a thing is in an undesirable physical state and should be transformed into a desirable one. For example, when a person thinks that the water in a cup is too cold, s/he will then propose a state-focused function, *to heat water*, that is, to increase the temperature of water. Note that a substance-transforming function can also be regarded as a special kind of state-focused function.

A behavior-focused function means that a thing has a (potentially) dynamic behavior that is regarded as dissatisfactory and therefore should be transformed. This kind of functions is often neglected in previous engineering design research. It is suggested that the description of a behavior-focused function should explicitly include the focused behavior, so that it can be easily understood. For example, because water can flow away, a behavior-focused function, *to store water*, should then be clearly indicated as *to prevent water from flowing away*.

An action-focused function means that a designer is dissatisfied with an action that one thing exerts on another, and therefore a desired function is needed to change the action. For example, a mechanical designer may think that the friction action of a machine seat on a rotating axle is too big and therefore propose an action-focused function, *to diminish the friction action of seat on axle*. Similar to behavior-focused functions, action-focused functions have also received little attention from engineering design society. A proof is that some designers even did not know how to explicitly describe the function of a lubrication component (Eckert, 2013).

A relation-focused function means that a designer is dissatisfied with the relation between two things in a world, and therefore a function is needed to transform the relation between them. A typical example is the aforementioned function, *to separate water from hair*, where what the designer is actually interested in is the location relation between water and hair (i.e., water and hair should not be in the same location), rather than a state change of either water or hair.

It is expected that this functional taxonomy can clarify our concept of function and can tell designers how to describe different kinds of functions. In addition, it can also be found that behavior or action is necessary for describing a function in some situations, which is different from what is suggested in existing design methodologies (i.e., only describing a function as a verb–noun pair).

4.3. A comparative analysis

Based on the understandings mentioned above, it is now possible to compare our scientific ontology based concept of function with those in existing engineering design research.

https://doi.org/10.1017/S0890060413000243 Published online by Cambridge University Press

Due to limited space, only three representative functional definitions are given below for comparison.

The first definition is from Pahl and Beitz (1996), who define function as a general relationship between the input and output of a system, aiming at performing a design task. This definition has served as the conceptual foundation of multiple functional reasoning approaches (e.g., in Campbell et al., 2000; Chakrabarti & Bligh, 2001; Chen et al., 2012; Nagel & Stone, 2012). A major problem with this definition is that it is not based on an explicit ontology. For example, it even does not have the concept of behavior. Another problem with this definition is that it is not suitable for the functions that do not deal with explicit input–output transformations (Umeda et al., 1996).

The second one is from Gero and Kannengiesser (2004), who have defined function as the purpose (teleology) of an artifact. However, because purpose is a purely subjective concept, treating function as purpose would make function become a purely subjective concept, which would make function ineligible an intermediate concept to bridge the gap between the subjective world and the objective world. As a result, it is often possible that such functions (i.e., purposes) cannot be represented with explicit physical states (e.g., to amuse passengers).

The third one is function as intended behavior (e.g., Goel et al., 2009). As mentioned before, the behavior concept in such research is more like our ontological concept of physical (i.e., objective) action. Therefore, it is fair to say that function in such research is regarded as intended objective action. Because intended objective actions are only part of objective actions, treating function as intended objective action would make function become a purely objective concept. As a result, such a concept of function then is insufficient to serve as an intermediate concept between the subjective world and the objective world.

Compared with the existing understandings of function described above, our concept of function does not have the mentioned limitations. For example, because our concept of function can deal with potential behaviors or actions, it can also represent the functions that do not deal with input–output transformations (e.g., *to prevent water from flowing away*); because our concept of functional action actually lies between the objective action set and the subjective action set (see Fig. 1), it is just an intermediate concept between the subjective world and the objective world, and therefore can bridge the gap between the human need domain and the physical solution domain. Therefore, our concept of function can serve as a more explicit and more reasonable concept foundation for design science.

5. CASE STUDY

The function definition of a civil aircraft type is employed here to illustrate the significance of an explicit concept of function. For the sake of commercial secrets, the name of the aircraft design company (ADC) is omitted here. Because civil aircrafts are very large and complex, aircraft companies are suggested to follow some systematic aircraft development guidelines to obtain airworthiness certificates with less difficulty.

The function definition of an aircraft type is a process that defines the functions of an aircraft type at the aircraft level and then decomposes them into more detailed functions. The ADC has invited some international experts, who are specialized in systematic aircraft design, to form an international design team to undertake the aircraft function definition work. Part of the function definition result is shown in Figure 2, where the aircraft functions are illustrated with three-layered function trees.

However, it is not difficult to find that there are multiple problems with this function definition result. For example, while many functions were described with transitive verbs, there were also some exceptions (e.g., *to move from airport A to airport B* and *to accelerate in air*); some function-related concepts (e.g., behavior and purpose) had been misunderstood as function (e.g., the behavior, *to accelerate in air*,

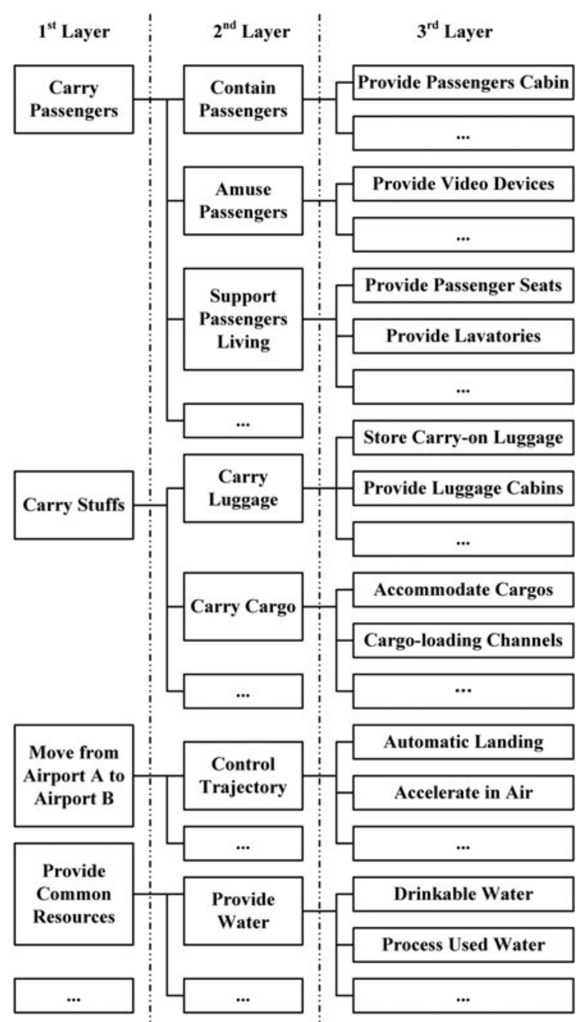

Fig. 2. The initial aircraft function definition result.

https://doi.org/10.1017/S0890060413000243 Published online by Cambridge University Press

Table 1. *Part of the revised aircraft function definition result*

Customer Need	Related World	(Potential) Dissatisfying Aspect	Function
To move from A to B	{Passengers}	At location A	Transport passengers from A to B
To walk in aircraft	{Passengers}	No space to move (if no lanes)	Allow passengers to move
To sit in aircraft	{Passengers}	To fall down (if not supported)	Prevent passengers from falling
To breathe	{O_2}	Not enough O_2	Make O_2
	{CO_2}	Too much CO_2	Remove CO_2
To carry luggage	{Luggage}	No (enough) containing space	Contain luggage
		To fall down (if not supported)	Prevent luggage from falling
		To slide away (if not fastened)	Prevent luggage from sliding
To eat food	{Food}	At low temperature	Heat food
		To decay (if not refrigerated)	Prevent food from decaying
	. . .	. . .	. . .
To drink water	{Drinkable water}	To flow away (if not contained)	Prevent water from flowing away
To keep warm	{Cabin air, outer air}	To cold cabin air through heat exchange (if not isolated)	Prevent outer air from cooling cabin air
To excrete	{Excreting passengers, other pass.}	At same location	Separate the excreting pass, from other pass.
	{Excretions}	To flow away (if not contained)	Prevent excretions from flowing to other places
	. . .	. . .	. . .
. . .	. . .	. . .	. . .

and the purpose, *to amuse passengers*); and many functional descriptions in the third layer (e.g., *to provide passenger seats* and *to provide lavatories*) were more like structural descriptions. Therefore, it can be concluded that the aircraft designers did not have an explicit concept of function.

To solve the above problems, the authors were invited to revise the functional definition result. A human need-driven approach is suggested to help aircraft designers revise the function definition result. The human need-driven approach involves four primary stages. The first stage is to define the human needs related to an artifact, which depends on how people will behave or interact with the artifact. The second stage is to derive the physical worlds (i.e., the objects of desired functions) that are related to those human needs. The third stage is to clarify the (possible) dissatisfying aspects of the physical worlds. The fourth stage is to define desired functions according to those dissatisfactions. Part of the new function definition results are shown in Table 1.

It can be found that the new aircraft function definition result is better than the previous one, and conforms well to our scientific ontology based concept of function. The functions are clearly associated with human needs through related physical worlds and (potential) dissatisfactions. Some functions that were previously described in an inappropriate way are now explicitly described. For example, the description *to move from (airport) A to B*, which actually describes an aircraft behavior, is now transformed as a state-focused function, *to transport passengers from A to B*; the description *to provide passengers' seats* is now redefined as a behavior-focused function, *to prevent passengers from falling down to the deck*; the description *to provide lavatories* is now related to multiple functions, such as a relation-focused function, *to separate excreting passengers from other passengers*, and a behavior-focused function, *to prevent excretions from flowing randomly into undesired locations*.

From this case study, it can be found that our concept of function is more explicit and more reasonable than existing ones, which has allowed designers to reach more explicit and precise aircraft function definition results. Almost all aircraft designers in the ADC agree that our concepts of behavior, action, and function are explicit and understandable, and can be applied to functional design practice.

6. CONCLUSION

Although function is regarded as a critical concept for design science, it still remains an ambiguous concept in both academic research and industrial practice. Based on Bunge's (1977) scientific ontology, this paper is devoted to developing an explicit concept of function for design science. The primary findings are as follows.

First, an ontological concept of behavior is clarified with the aid of Bunge's scientific ontology. Its primary ontological commitments are provided to help designers understand this concept, together with a comparative analysis.

Second, the ontological concept of (physical) action is imported from scientific ontology to design science. Its primary ontological commitments are also provided, together with an analysis of the differences between behavior and action, and the differences between physical action and mental action.

Third, based on scientific ontology, a more explicit and precise concept of function has been defined as a special kind of desired mental action, aimed either at transforming an objective (i.e., physical) world of interest from a dissatisfactory state to a desirable one or at preventing an objective (i.e., physical) world from changing into a undesirable state.

https://doi.org/10.1017/S0890060413000243 Published online by Cambridge University Press

The primary commitments of function are provided, together with an ontology-based functional taxonomy. The differences between function and other related concepts (e.g., behavior and action) are also discussed.

An aircraft function definition case has been employed to demonstrate the proposed concept of function. Based on our scientific ontology based concept of function, it can be seen that aircraft designers can now define the functions of an aircraft type in a more explicit, precise, and reasonable way. It is expected that our function-related discussions here can give academic researchers a more explicit and precise concept of function for developing design science, and design practitioners a more stable concept for applying design science to industry.

ACKNOWLEDGMENTS

We acknowledge Professor Roozenburg from TU Delft for reminding us of Bunge's scientific ontology, as well as the anonymous reviewers and the Guest Editors for their constructive suggestions. This research is supported by the Natural Science Foundation of China (Grants 50975173, 51205247, and 50935004), the Ministry of Science and Technology of China (Grant 2008AA04Z108), and the Science and Technology Commission of Shanghai Municipality (Grant 09QA1402800).

REFERENCES

Bobrow, D.G. (1984). Qualitative reasoning about physical systems: an introduction. *Artificial Intelligence 24(1–3)*, 1–5.

Bunge, M. (1977). *Treatise on Basic Philosophy—Ontology I: The Furniture of the World*. Dordrecht: Reidel.

Campbell, M.I., Cagan, J., & Kotovsky, K. (2000). Agent-based synthesis of electromechanical design configurations. *ASME Journal of Mechanical Design 122*, 61–69.

Chakrabarti, A., & Bligh, T.P. (2001). A scheme for functional reasoning in conceptual design. *Design Studies 22*, 493–517.

Chen, Y., Lin, Z.Q., Feng, P.E., & Xie, Y.B. (2007). Understanding and representing functions for conceptual design. In *Proc. 16th Int. Conf. Engineering Design* (Bocquet, J.C., Eds.), Paper No. 223. Paris: Design Society.

Chen, Y., Liu, Z.L., & Xie, Y. (2012). A knowledge-based framework for creative conceptual design of multi-disciplinary systems. *Computer-Aided Design 44*, 146–153.

Chen, Y., Zhang, Z.N., & Liu, Z.L. (2011). Towards a scientific function–behavior transformation model. *Proc. 18th Int. Conf. Engineering Design. Vol. 2: Design Theory and Research Methodology* (Culley, S.J., Hicks, B.J., McAloone, T.C., Howard, T.J., & Reich, Y., Eds.), pp. 51–60. Copenhagen: Design Society.

Dorst, K., & Vermaas, P.E. (2005). John Gero's function–behavior–structure model of designing: a critical analysis. *Research in Engineering Design 16*, 17–26.

Eckert, C. (2013). That which is not form: the practical challenges in using functional concepts in design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 217–232 [this issue].

Erden, M.S., Komoto, H., Van Beek, T.J., D'Amelio, V., Echavarria, E., & Tomiyama, T. (2008). A review of function modeling: approaches and applications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 22*, 147–169.

Gero, J.S., & Kannengiesser, U. (2004). The situated function–behavior–structure framework. *Design Studies 25(4)*, 373–391.

Goel, A.K. (2013). A 30-year case study and 15 principles: implications of an artificial intelligence methodology for functional modeling. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 203–215 [this issue].

Goel, A.K., Rugaber, S., & Vattam, S. (2009). Structure, behavior, function of complex systems: the structure, behavior and function modeling language. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 23*, 23–35.

Guarino, N. (1995). Formal ontology, conceptual analysis and knowledge representation. *International Journal of Human–Computer Studies 43*, 625–640.

Hubka, V., & Eder, W.E. (1996). *Design Science*. London: Springer–Verlag.

Nagel, J.K.S., & Stone, R.B. (2012). A computational approach to biologically inspired design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 26(2)*, 161–176.

Pahl, G., & Beitz, W. (1996). *Engineering Design: A Systematic Approach* (2nd ed.). London: Springer–Verlag.

Society of Automobile Engineers Aerospace. (2010). *Aerospace Recommended Practice (ARP-4754A): Guidelines for Development of Civil Aircraft and Systems*. Warrendale, PA: Author.

Suh, N.P. (2001). *Axiomatic Design: Advances and Applications*. New York: Oxford University Press.

Umeda, Y., Ishii, M., Yoshioka, M., Shimomura, Y., & Tomiyama, T. (1996) Supporting conceptual design based on the function–behavior–state modeler. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 10*, 275–288.

Verein Deutscher Ingenieure. (1993). *Systematic Approach to the Development and Design of Technical Systems and Products,* VDI 2221. Düsseldorf: Verein Deutscher Ingenieure.

Vermaas, P.E. (2013). The coexistence of engineering meanings of function: four responses and their methodological implications. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 27(3)*, 191–202 [this issue].

Yong Chen is an Associate Professor of engineering design in the School of Mechanical Engineering at Shanghai Jiao Tong University. He received his bachelor and PhD degrees from Zhejiang University. He joined Shanghai Jiao Tong University as a postdoc in 2004. He was a visiting scholar in the IMPACT Laboratory at University of Southern California for 1 year. Dr. Chen is interested in many aspects of engineering design research, in particular conceptual design, creative design, design knowledge reuse, and computer-aided design.

Zhinan Zhang is currently a Postdoctoral Researcher in the School of Mechanical Engineering at Shanghai Jiao Tong University. He received his PhD degree at the same university in 2011. Dr. Zhang's research interests include design theory and methodology, knowledge management, and engineering tribology.

Jian Huang is currently a PhD student in the School of Mechanical Engineering at Shanghai Jiao Tong University. He received his bachelor degree in 2008 from Wuhan University. His research interests include knowledge-based design and computer-aided design.

Youbai Xie is a Professor in the School of Mechanical Engineering at Shanghai Jiao Tong University. He is the Director of the Institute of Modern Design of Shanghai Jiao Tong University. Dr. Xie is an academic member of the Chinese Academy of Engineering. His research interests include engineering tribology, design science, and knowledge management.