Explicating concepts in reasoning from function to form by two-step innovative abductions

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Abstract

The mechanism of design reasoning from function to form is suggested to consist of a two-step inference of the innovative abduction type. First is an inference from a desired functional aspect to an idea, concept, or solution principle to satisfy the function. This is followed by a second innovative abduction, from the latest concept to form, structure, or mechanism. The intermediate entity in the logical reasoning, the concept, is thus made explicit, which is significant in following and understanding a specific design process, for educating designers, and to build a logic-based computational model of design. The idea of a two-step abductive reasoning process is developed from the critical examination of several propositions made by others. We use the notion of innovative abduction in design, as opposed to such abduction where the question is about selecting among known alternatives, and we adopt a previously proposed two-step process of abductive reasoning. However, our model is different in that the two abductions used follow the syllogistic pattern of innovative abduction. In addition to using a schematic example from the literature to demonstrate our derivation, we apply the model to an existing, empirically derived method of conceptual design called "parameter analysis" and use two examples of real design processes. The two synthetic steps of the method are shown to follow the proposed double innovative abduction scheme, and the design processes are presented as sequences of double abductions from function to concept and from concept to form, with a subsequent deductive evaluation step.

Keywords: Abduction; Design Reasoning; Innovative Abduction; Parameter Analysis

1. INTRODUCTION

It is widely accepted that design begins with a function, a need to be satisfied, and terminates with form, a description of a proposed artifact, which is a blueprint for its manufacture that includes the composition, shape, materials, dimensions, and so forth. However, how exactly does form follow function? What is the type of reasoning involved? Where does the form come from? Is the form inferred directly from the function using some sort of rule set? Are there any intermediate steps in the reasoning that are more or less explicit? The paper aims at clarifying the reasoning from function to form in design through critical examination of prior proposals, which apply the concept of abduction. Special reference is made to the conceptual design method of parameter analysis.

Ullman (1992, p. 140) states that reasoning from function to form is done by a double mapping process: first from function to concept, and then from concept to form. His method for conceptual design then follows the German-school sys-

tematic design (Pahl & Beitz, 1984), which prescribes a comprehensive functional decomposition stage, followed by finding working principles (concepts) for the various subfunctions and combining them into an overall concept (the principal solution) with the help of a morphological chart. The working principles usually consist of "physical effects + form," while the principal solution is defined as an idealized representation of the structure that defines those characteristics that are essential for the functioning of the artifact (Roozenburg, 1993). Many variations on this approach appear in widely used design textbooks, including those by Otto and Wood (2000) and Ulrich and Eppinger (2007). Borrowing from artificial intelligence (AI) and search techniques, this approach may be regarded as working "breadth-first" because the comprehensive functional decomposition stage has to be completed before moving on to the next level, the morphological chart, and this in turn has to be completed for all the subfunctions before initiating the stage of combining working principles into overall concepts.

In contrast, other design paradigms emphasize the sequential and iterative character of applying the reasoning from function to form. Suh's axiomatic design framework consists

of the functional space and the physical space (Suh, 1990). The former contains functional requirements (FRs) and the latter design parameters (DPs). Mapping FRs into DPs is the core of the design process; however, because there can be many alternative ways of doing this, the design axioms provide the principles to be satisfied by the mapping to produce good designs. Suh does not expand on how solution concepts or ideas are generated; rather, he uses many examples of design problems and their solution ideas to support the notions of FRs, DPs, and the two axioms. The important point, however, is that the function to form mapping is applied repeatedly: new functional requirements are constantly generated from previous design parameters, and so forth.

Another framework, function–behavior–structure (FBS; Gero & Kannengiesser, 2004), identifies several processes within design, such as transforming functional requirements into expected behaviors, transforming expected behaviors into solution structures, deriving actual behaviors from structures, comparing derived with expected behaviors, and responding to unsatisfactory behaviors by reformulating the design space (changing the structure, behavior, or function). These design steps are again applied repeatedly, as with Suh's (1990) model. In addition, common to the axiomatic design and FBS models is that they do not use the notion of "concept," in the sense of underlying solution ideas, as an explicit constituent of the reasoning process. This may be because these models are descriptive (they tell how design is carried out in practice), so they emphasize what is apparent to an outside observer of designers: needs (functions) are turned into physical solutions, while the ideas (concepts) remain implicit, in the designer's mind.

A need–function–principle system model has been proposed recently for conceptual design (Chen et al., 2015a, 2015b). A clarification stage converts subjective needs into objective functions, followed by a synthesis stage to find abstract principles for satisfying the functions. The abstract principles consist of combinations of action classes and behavior classes, which are generalized actions and behaviors, respectively. Next comes an embodiment stage, where action classes and behavior classes are instantiated as a system (i.e., structure) having corresponding specific actions and behaviors. The actions and behaviors are verified in an analysis stage, followed by a prediction stage to identify unintended side effects and possibly generate new functions for the next design cycle. This model clearly includes explicit reasoning at the level of concepts in the form of abstract principles, which are similar to systematic design's working principles.

2. THE PARAMETER ANALYSIS METHOD OF CONCEPTUAL DESIGN

2.1. Description of the method

Parameter analysis (PA), the conceptual design method discussed in this article, is different from the other methods in that it makes the concepts the pivot about which the design

process revolves. Contrary to systematic design, but similar to axiomatic design, FBS, and need–function–principle, PA presents the design process as a repeatedly applied sequence of steps, not a single pass through major stages. PA originally started as an empirically derived descriptive model, in which the designer moves back and forth between the space of ideas (concept space) and the space of physical realizations (configuration space; Li et al., 1980). It was later developed into a prescriptive model, facilitating the interspace mental movement by three distinct steps (Kroll et al., 2001; Kroll, 2013). *Parameter identification* (PI) corresponds to finding a "parameter" (concept or idea) for resolving a functional issue with the evolving design. This concept is mapped into form by the *creative synthesis* (CS) step, and the latest configuration is tested by an *evaluation* (E) step. This last step often results in new functional issues (unsatisfactory or undesirable behavior) to be resolved, so the process continues until an acceptable solution has been reached.

Kroll et al. (2014) have rigorously interpreted the reasoning steps in PA by applying the concept–knowledge (C-K) theory of design (Hatchuel & Weil, 2009) to them. It was shown that the PI step amounts to adding an "ideational" attribute to the evolving design, while the CS step adds a "structural" attribute to it. Overall, a design process that incorporates cycles of reasoning from function to concept and from concept to configuration unfolds. It should be noted, however, that the term *concept* in C-K refers to the description of the tentative evolving artifact, and not to a solution idea as in PA.

In a more recent work (Kroll & Koskela, 2016), we studied the method of PA from the perspective of the prototheory of design, which is based on the method of geometric analysis, as suggested by Aristotle. It was concluded that certain design "moves" could be explained as being deductive, some as regressive, but others were more difficult to cast in this framework and were characterized as being compositional or transformational/interpretational. As shown in Figure 1, deductive reasoning (the E step) is used to infer behavioral aspects from the evolving configuration, from which a functional aspect to be addressed next is derived. This function is the input to PI, where a concept or idea ("parameter") is sought to satisfy it, and this is often done by transforming the problem or interpreting it in a different way. Once a concept has been identified, another regressive inference takes place to create a configuration (hardware representation or form) that realizes the concept. The second CS step in Figure 1 represents composition: the integration of the latest configurational solution in the overall form of the design artifact. The main focus of the current paper is on the PI and first CS steps, as they stand for the core operations in design: reasoning from function to concept, and reasoning from concept to form, respectively.

PA is unique in that it places the most emphasis on the PI step. The reasoning at the conceptual level is claimed to be so important that "parameters" (ideas, concepts, operating principles, underlying physical effects, analogies, etc.) have to be stated explicitly. The E step is considered second in impor-
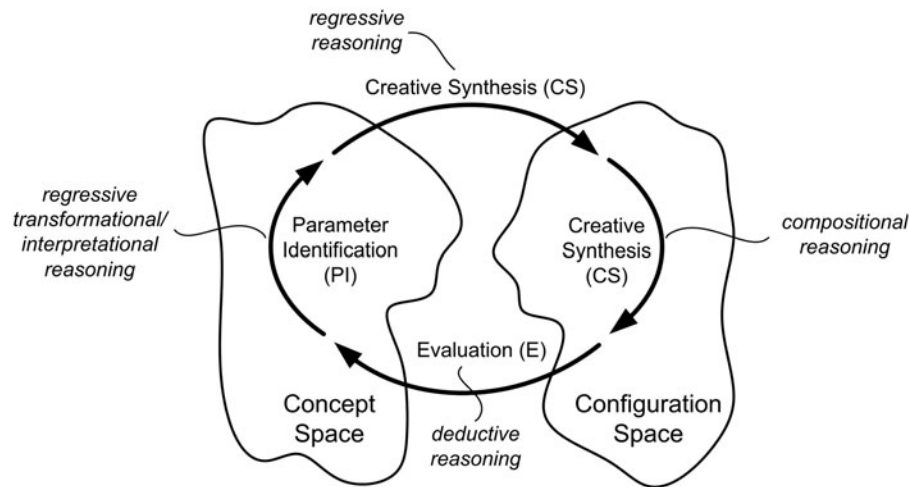
Fig. 1. The parameter analysis process consists of repeatedly moving between concept space and configuration space by applying parameter identification (PI), creative synthesis (CS), and evaluation (E).

tance, because it involves abstracting from a particular problem to new functional issues at the conceptual level. The actual step of giving form to the design, CS, is ranked the least important, because intermediate configurations are needed mostly to facilitate the evaluation, and any unsatisfactory characteristic of a configuration will be mended in the next cycle. Therefore, although the outcome of the design process is certainly a configuration, the philosophy of PA is that the reasons, justifications, and derivations behind the configuration are indispensable when it comes to presenting a design solution or studying the process of designing.

2.2. Examples of partial PA processes

The following two examples are reproduced from Kroll (2013) and Kroll et al. (2014), respectively. They represent design processes that are different in nature. The first is "linear" in the sense of pursuing a single fundamental concept and incrementally improving it, while in the second, various technologies are explored until a breakthrough takes place and a totally new concept emerges.

2.2.1. Example 1: Designing a sensitive tiltmeter

A device was needed for measuring very small angles of tilt of the ground with respect to the local gravity vector. The inventor's account of his thought process as PA follows, with Figure 2 showing a schematic of the design:

PI$_1$: A simple pendulum can be used to measure tilt.

CS$_1$: A very long device, of the order of 50 m, will be required for the small angles that need to be measured.

E$_1$: This is too long. A physically short pendulum ($\sim$0.5 m) that behaves as if it were long is needed.

PI$_2$: A simple pendulum being displaced laterally can be thought of as a spring, that is, producing a restoring force

proportional to the displacement. Stating that the pendulum needs to be very long is equivalent to requiring a very soft spring (small spring constant k). However, how can a small k be obtained when the physical dimensions should be kept small? Let us use the difference between two large spring constants (short pendulums) to yield a small k (effectively long pendulum). This requires a negative spring, that is, one that produces a force in the direction of the disturbance, and this can be provided by unstable devices such as an inverted pendulum.

CS$_2$: The configuration consists of two coupled pendulums, one simple and one inverted; the resultant spring constant is made small but positive, thus producing the desired high sensitivity while being stable.

E$_2$: This may work, but friction in the joints needs to be reduced to ensure the required sensitivity.
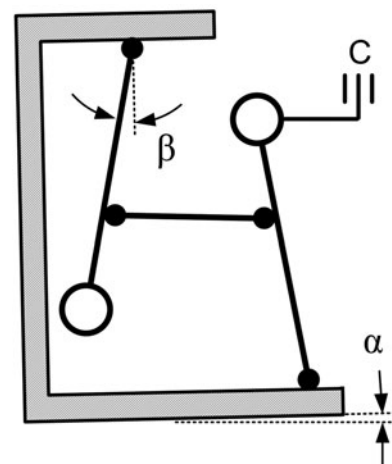
Fig. 2. A schematic of the tiltmeter with input angle α producing a response β where $\beta \gg \alpha$. The large circles are weights, small solid circles are flexural hinges, the lines represent stiff rods, and C is a differential capacitor transducer.

PI_3: Minimize friction by using rolling contact instead of sliding.

CS_3: Flexural hinges with near-zero resistance are implemented in the joints.

E_3: Displacement measurement, also without friction, is needed.

PI_4: Use a noncontact technology for displacement measurement.

CS_4: A capacitor-type sensor is added to the design.

E_4: . . . .

2.2.2. Example 2: Designing decelerators for airborne sensors

A means of decelerating airborne sensors for monitoring air quality and composition was needed. The sensors were to be released at about 3000 m from a container carried by a light aircraft, so compact packing was required, and stay in the air for at least 15 min. A partial description of the designers' PA process follows:

PI_1: Deceleration can be produced using a flexible parachute.

CS_1: A 150-mm diameter hemispherical parachute, connected to the sensor with cords.

E_1: Drag force is okay and compact packing can be done by folding, but the parachute may not open because there is not enough "pull" on it, and the cords may tangle.

PI_2: A rigid parachute may be used to generate the drag force, eliminating the deployment problem.

CS_2: A 150-mm diagonal square pyramid with the sensor rigidly attached.

E_2: Drag force is okay but compact packing is impossible because these configurations cannot nest inside each other.

PI_3: Use a frame + flexible sheet construction that can fold like an umbrella, and use a spring for opening.

CS_3: Lightweight skeleton made of plastic or composite materials with "Saran wrap" stretched and glued onto it. Hinges and slides allow folding. A spring facilitates opening.

E_3: Drag force and compact packing are okay, but this structure is unreliable and expensive to manufacture because of the many moving parts.

PI_4: Looking at the problem from an energy viewpoint instead of producing retarding force, the sensor's potential energy can be dissipated over a longer distance by a smaller drag force. Use a small spiraling glider.

CS_4: Wings with a span of 200 mm and a small twist to produce a 30-m diameter spiral trajectory. The wings are made of Styrofoam and the sensor attached with plastic clips, as shown in Figure 3.

E_4: . . . .
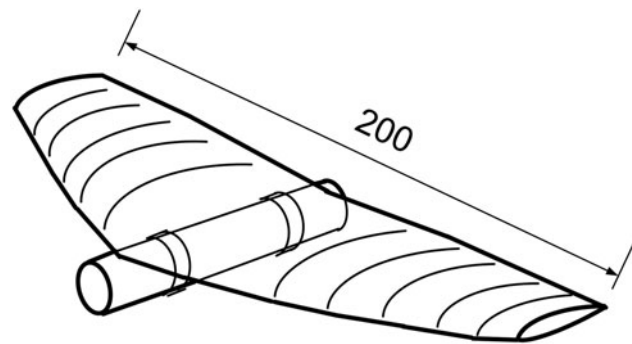
Fig. 3. A schematic of a small glider whose fuselage is the sensor to be decelerated.

2.3. Summary

The examination of prior theoretical models of design showed that there is little agreement regarding how the reasoning from function to form occurs. The examples based on PA, which is a practical method that has been taught and practiced for over two decades, demonstrate the type of reasoning that takes place: PI represents reasoning from function (what should be done to satisfy a need or to improve an evolving design) to concept ("parameter" in PA terms, which is the idea, technology, physical principle, etc.) to be used to attain the functional goal. CS starts with the latest concept and seeks to realize it in form, what is called configuration in PA. In addition to these two regressive reasoning steps, E is clearly deductive, of the "given structure, find behavior" type. However, how can we characterize the PI and CS steps better in terms of the entities and reasoning involved so as to improve our understanding of the function to form reasoning in design? To answer this question, we need to consult a logic-based framework.

3. DESIGN ABDUCTION

Regressive inferences in design are of particular interest because they involve heuristic reasoning and intuition, notions that are sometimes associated with the type of inference called abduction. For example, Cross (2006, p. 33) identified abductive reasoning with concepts of intuition, and Dew (2007), with creativity and subconscious activities. Peirce (1994) is attributed with proposing that abduction is a form of "synthetic" reasoning (together with induction, but different from the "analytic" reasoning of deduction), while focusing on scientific explanation. Researchers still disagree on the exact nature of induction (Vickers, 2013), and on abduction there are differing views although this concept has been discussed in philosophy of science since the 1940s (e.g., Burks, 1946).

Schurz (2008) presents a thorough classification of abduction patterns, all of which are "special patterns of inference to the best explanation." He identifies four main types of abduction (and subcategories for two of them) based on three

dimensions. The main dimension is the type of hypothesis (conclusion) abduced. The other two are the type of evidence to be explained and the cognitive mechanism driving the abduction. Schurz refers to "the official Peirce abduction schema" as "factual abduction" of the following structure:

Known Law: IF Cx THEN Ex
Known Evidence: Ea has occurred
_____

Abduced Conjecture: Ca could be the reason (1)

Investigations of abduction in relation to design have mostly been carried out by scholars in design theory and AI. Both streams of research are briefly discussed in the following. In design theory, March (1976) seminally suggests that abduction, which he calls "productive reasoning," is the key mode of reasoning in design. He also points to the confusion and misunderstanding created by not distinguishing between scientific and design hypotheses, and between logical propositions and design proposals. Whereas the goal of science is to establish general laws, he says, design is concerned with realizing a particular outcome. The pattern of abduction proposed by March is the following: from certain characteristics that are sought, and on the basis of previous knowledge and models of possibilities, a design proposal is put forward.

Roozenburg (1993) discusses in depth the question whether the reasoning toward a tentative description of a design follows the conventional view on abduction, or whether it should be defined differently. He argues that the commonly presented view, especially in AI literature, deals with "explanatory abductions," which are good for diagnosis or troubleshooting, but that the core of design reasoning follows another type of abduction, for which he proposes the terms "innovative abduction" and "innoduction" (Roozenburg & Eekels, 1995, chap. 4). In fact, says Roozenburg (1993), Habermas (1978, pp. 147–148) distinguished[1] between explanatory abduction as in (1) and innovative abduction, in which the law is not known and needs to be inferred together with the presumed reason for the evidence, and it was March who did not make that distinction.

A more recent paper by Dorst (2011) proposes yet another view on design abduction. It claims that there are two types of abduction relevant to design: *abduction-1*, which follows a similar pattern to (1), and *abduction-2*, which is comparable to Roozenburg's innoduction. Furthermore, Dorst suggests chaining these two inferences into a single reasoning step, which is the core of "design thinking." Chen et al. (2015a, 2015b) also present a two-step reasoning process, from function to principle and from principle to system. They explain that both are "implicit abductions" or innoductions, because they lack sufficient premises for generating only one result. Along with Roozenburg's introduction of the concept of innovative abduction and Dorst's and Chen et al.'s adoption of it, other design scholars still maintain Peirce's view and ap-

ply his "process of scientific inquiry," consisting of cycles of abduction, deduction, and induction, to the area of design (e.g., Pauwels et al., 2013).

In AI-oriented research on design abduction, the emphasis has been on computable abduction models. To some extent this work is overlapping with and influenced by design theory research on abduction. For example, Goel (1988) proposes to extend March's model if we wish to use it in knowledge-based systems. His argument is based on the fact that the laws (also called rules or knowledge) can have different logical natures (e.g., universal or statistical), and this affects the meaning of the abduction pattern. However, the work led by Takeda et al. (1990) on design abduction seems to be based on insights into design, and the connection to Peirce's seminal work on abduction in science is looser. Abduction is defined as a process making integrated hypotheses and theories to explain given facts (Takeda, 1994), a definition that goes beyond Schurz' classification of abduction (Tomiyama et al., 2003). Analogical reasoning is applied for computationally supporting abduction (Takeda et al., 2003).

To conclude, it seems that abduction has the potential to explain design moves in which new solutions are created, in general, and the PI and CS steps of PA in particular. For that purpose, we shall now examine both Roozenburg's and Dorst's models.

4. ROOZENBURG'S MODEL OF A SINGLE INNOVATIVE ABDUCTION

4.1. The syllogistic form

Explanatory abduction, also called "presumption of fact," is actually a reversal of deduction, says Roozenburg (1993). In deduction we have the following logical expression:

$p \rightarrow q$ (a given rule, IF p THEN q)
p (p is a given fact, a case or cause)
_____

q (q is the conclusion, the result) (2)

and reversing it gives

$p \rightarrow q$ (a given rule, IF p THEN q)
q (q is a given fact, a result)
_____

p (p is the conclusion, the case or cause) (3)

Expression (3) is the definition of explanatory abduction, similar to (1), where the conclusion is a plausible cause. According to Roozenburg, pattern (3) is not the main reasoning form in design, where the only given is a desired result, and both the rule and the cause need to be discovered. His *innovative abduction* therefore follows the pattern:

q (q is a given fact, a desired result)
_____

$p \rightarrow q$ (a rule to be inferred first, IF p THEN q)
p (p is the conclusion, the cause, that immediately follows) (4)

_____

[1] This distinction by Habermas invites critical comments; see Section 7.2.

Pattern (4) is the real abduction in design because it represents reasoning from a *function*, a desired result or purpose, to *form* and *use*. Form and use are the "principal solution," the structure of the artifact and its way of use that define its function.

4.2. Demonstration: Designing a kettle

Roozenburg demonstrates innovative abduction through the example of designing the first ever kettle. The purpose, *function*, is to boil water. The *mode of action* (defined as "using laws of nature to produce a desired effect"), or functional behavior, is heating the bottom of the kettle and conducting the heat to the water inside. This will be facilitated by the *way of use* (also called "actuation") of filling the kettle with water and placing it on a burner. Finally, to allow all this, the kettle must have a specific *form*: hemisphere with opening at the top and metal construction.

Now that there are four distinct entities involved in the reasoning (*function, mode of action, way of use*, and *form*), Roozenburg groups together *form* and *way of use* into one entity, claiming that they always go hand in hand, so he writes:

$$form + way\ of\ use\ \rightarrow\ mode\ of\ action\ \rightarrow\ function \qquad (5)$$

or in other words, hemisphere and metal + fill with water and place on burner → heat bottom of kettle and conduct heat to the water inside → boil water.

Next, the intermediate result (*mode of action*) in expression (5) can be omitted, so what is left is

$$form + way\ of\ use \rightarrow function \qquad (6)$$

or, hemisphere and metal + fill with water and place on burner → boil water.

The *function* (boil water) is given in design, says Roozenburg. What needs to be designed is usually considered to be the *form* (hemisphere and metal). However, a description of *form* is not enough to predict the behavior that fulfills the *function*. The behavior (*mode of action*) depends on *form* but also on the *way of use*. Thus, the designer needs to develop ideas on *way of use* together with *form*. It follows that the "kernel of design" is the reasoning from *function* to *form + way of use*. This, according to Roozenburg, follows the same pattern of reasoning as Habermas' innovative abduction, expression (4), if we define *p* as the combined description of *form + way of use*:

q	boil water (the only given is the *function*)
$p \rightarrow q$	IF hemisphere and metal + fill water and place on burner THEN boil water (IF *form + way of use* THEN *function*; the rule to be inferred first)
p	hemisphere and metal + fill water and place on burner (*form + way of use*; the second conclusion) (7)

The meaning of the last logical inference is that if you want to boil water, you need to "discover" the first conclusion (hemisphere and metal *form* + filling water and placing on burner *way of use* → boil water *function*), and immediately you will get the second conclusion (hemisphere and metal *form* + filling water and placing on burner *way of use*). The second conclusion constitutes the principal solution to the design problem.

4.3. Is a single abduction enough?

The question regarding Roozenburg's claim is whether the designer who wants to boil water can generate the "rule" in the first conclusion directly, without reasoning about the *mode of action* (heating the bottom of the kettle and conducting the heat to the water inside) first. Roozenburg's description does not include the *mode of action* explicitly, assuming perhaps that somehow the designer has gained the insight on using this specific *mode of action*, which is the main characteristic of the principal solution, and now proceeds according to pattern (7). Roozenburg's presentation of abduction can be modified to expression (8), where the underlined addition of the *mode of action*, the operating principle, makes it explicit:

q	boil water by heating the bottom of a container and conducting the heat to the water (*function* and *mode of action*)
$p \rightarrow q$	IF hemisphere and metal + fill water and place on burner THEN boil water by heating the bottom of a container and conducting the heat to the water (the first conclusion)
p	hemisphere and metal + fill water and place on burner (the second conclusion) (8)

However, this raises two new questions: where did the mode of action come from in the first place and should it not be an explicit abductive step by itself in the description of the "kernel of design" and does pattern (8) represent what really happens during design?

4.4. From single to double abductions

To answer these questions, let us try to imagine the thought process while designing the (first ever) kettle. We need to design a device to boil water (but in a certain context, of having at our disposal a burner, and the boiled water will be used to make tea, as opposed, for example, to generating steam in a sauna). What operating principle can we use? Here is an idea: we need some sort of container that can be filled with water and placed over the burner. Then the bottom of the container will be heated, and the heat will be conducted to the water inside (note that we came up with a *mode of action*, heating the bottom of the water container and conducting the heat to the water, and a *way of use*, filling the container with water and placing it on the burner). Now that we have decided on these (*mode of action + way of use*), we ask ourselves what *form* we should give the device to work properly (that is, a

form that when used as intended, filled with water and placed on a burner, will result in the intended *mode of action*, conducting the heat to the water). The answer now is, use a hemisphere with opening at the top and make it out of metal.

The reasoning above is clearly from *function* to *mode of action + way of use* first, followed by reasoning from *mode of action + way of use* to *form*. Roozenburg represents this process as a single innovative abduction, wherein the *mode of action* is implicit, so it gives the impression that the main idea (*mode of action*) is not part of the abduction at all. Moreover, Roozenburg combines *way of use* with *form* into a single entity, as if they are inseparable.

A more correct way to represent the above reasoning process may be by a two-step or double innovative abduction to capture that two distinct inferences are carried out:

First step:

q	boil water (the *function*)
$p \rightarrow q$	IF fill water and place on burner so heat is conducted to water THEN boil water (the first conclusion: *way of use + mode of action → function*)
p	fill water and place on burner so heat is conducted to water (the second conclusion: *way of use + mode of action*) (9)

Second step:

q	fill water and place on burner so heat is conducted to water (the newly generated *way of use + mode of action* is now the given)
$p \rightarrow q$	IF hemisphere with opening and metal THEN fill water and place on burner so heat is conducted to water (the first conclusion: *form → way of use + mode of action*)
p	hemisphere with opening and metal (the second conclusion: *form*) (10)

To summarize, the above two-step reasoning allows inferring from *function* to an idea, concept, or solution principle (shown as *way of use + mode of action*) first, and from that principle to the *form*. In general, we can say that each innovative abduction reasoning step of pattern (4) involves <u>two</u> entities, *p* and *q*, but design reasoning should involve <u>four</u> entities: *function, mode of action, way of use*, and *form*. Although we claim that *mode of action* and *way of use* seem to frequently show together,[2] so they can be counted as one entity, the three remaining entities still require two inferences, not one. What Roozenburg did is actually leave out *mode of action* and group *form* and *way of use* into one entity, claiming that together they are the sought solution, so he could reduce the problem to a two-entity single abduction.

Support for the insight that four entities should be involved in describing design reasoning can be found in the work of Zeng and Cheng (1991), which Roozenburg claims arrived at similar

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² Further elaboration on this issue can be found in Section 7.1.

conclusions to his. Zeng and Cheng argue that design reasoning involves three entities: *form, function*, and *environment*, and that the *environment* consists of two entities: *laws of nature* and *actions of nature*. If *laws of nature* are Roozenburg's *mode of action*, and *actions of nature* are his *way of use*, then we have a one-to-one correspondence of the four entities.

5. DORST'S MODEL OF DOUBLE ABDUCTION

5.1. The syllogistic form

Dorst (2011) also must have realized that a single abduction cannot explain "design thinking." His presentation of abduction revolves around the following logical expression:

what (the artifact) + *how* (the working principle) → *value* (aspired). (11)

In this expression, the (aspired) *value* is always given. If the *how* is also given, the designer generates the *what* by a so-called *abduction-1*, which is precisely the *explanatory abduction* of pattern (3). Dorst calls this case "conventional ('closed') problem-solving that designers often do." If, however, the *how* is not given, then this is a more "open" problem for which the designer needs to decide on both the working principle and the artifact. This is accomplished by *abduction-2*, as in pattern (4), which is the same as Roozenburg's innovative abduction. *Abduction-2* is carried out by first developing or adopting a "frame" (after Schön, 1983), which is a "general implication that by applying a certain working principle we will create a specific value." With the help of framing, *abduction-2* takes place according to the following pattern:

q	(*q* is the given desired *value*)
$p \rightarrow q$	(IF *how* THEN *value*, the first conclusion)
p	(*how*, the second conclusion) (12)

When a possible or promising frame has been proposed and the *how* is known, says Dorst, *abduction-1* can take place to design the *what*, the artifact.

5.2. What type of second abduction?

Dorst maintains that the second abductive step in design reasoning is a form of *abduction-1*. Let us now test that by applying Dorst's two-step reasoning process (*abduction-2* followed by *abduction-1*) to Roozenburg's kettle example. Surely, the *value* in expressions (11) and (12) corresponds to *function*, and the *what* in (11) corresponds to *form* (Dorst calls it the "object" or "thing"). The *how*, therefore, must stand for the *way of use + mode of action* (also to be in agreement with Zeng and Cheng on having four entities involved in design reasoning). If we set *value* = "boil water" as the only known fact, *abduction-2* may yield a possible working principle, a *how*, which is the following *way of use + mode of action:* "fill water and place on burner so heat is conducted to water." Thus far this is identical to expression (9).

Now we need to design the *what*, or *form*, and Dorst suggests that this will be done by *abduction-1* because we know the *value* and *how* in expression (11). For *abduction-1* to take place according to pattern (3), however, the conclusion should appear as the premise of the given rule, and this does not seem to be the situation here. The *what* is still unknown (recall that this is the first kettle ever), and of course this is why this kind of *explanatory abduction* cannot be the main form of reasoning in design. The only possibility is to use *abduction-2* again, starting with the only known, the *how* found in the previous step. Then a rule is sought for tying together a *what* (form) to this given *how* (working principle), and thus inferring that *what*. The resulting inference is identical to expression (10).

6. THE DOUBLE INNOVATIVE ABDUCTION IN PARAMETER ANALYSIS

We showed how Roozenburg's and Dorst's models of reasoning from *function* to *form* can be changed to two *innovative abduction* (or *abduction-2*) inferences, as in (9) and (10). The proposed modification allows comparing this model with PA. As explained and demonstrated earlier, PI is reasoning from a functional aspect to a solution principle, which is equivalent to the first innovative abduction as in (9). The solution principle (concept) consists of *way of use + mode of action*. The second step is CS, where the reasoning begins with the solution principle derived in PI and ends with a configuration, structure, or form, as in (10). Overall, we obtain the double mapping *function → concept → form*.

The examples of PA described in Section 2.2 can easily be presented as such double abductions. The cycles of double innovative abductions, corresponding to the PI and CS steps with the deductive E step occurring after each cycle, as applicable to Example 1, is shown by expressions (13) to (20):

PI_1:

q	measure small tilt (the *function*; specified by the need definition)
$p \rightarrow q$	IF a simple pendulum is used THEN small tilt can be measured (the first conclusion: *way of use + mode of action → function*)
p	a simple pendulum (the second conclusion: *way of use + mode of action*) (13)

CS_1:

q	a simple pendulum (the newly generated *way of use + mode of action* is now the given)
$p \rightarrow q$	IF the pendulum is 50 m long THEN the required resolution will be obtained (the first conclusion: *form → way of use + mode of action*)
p	a 50-m long pendulum (the second conclusion: *form*) (14)

At this point, the deductive step E_1 concludes that the pendulum is too long, and a short pendulum that behaves as if it were long is needed. This becomes the given function to be realized in the next cycle:

PI_2:

q	a short pendulum that behaves as if it were long
$p \rightarrow q$	IF a short pendulum is like a stiff spring and two large spring constants are subtracted to give a small difference THEN a long-pendulum behavior will result
p	small difference between two large spring constants (15)

CS_2:

q	small difference between two large spring constants
$p \rightarrow q$	IF two short pendulums, one simple and one inverted, are coupled THEN a small difference between their spring constants will be obtained
p	two short pendulums, simple and inverted, coupled by a hinged crossbar (16)

E_2 now deduces that for the device to work properly, joint friction needs to be reduced:

PI_3:

q	reduce joint friction
$p \rightarrow q$	IF rolling contact replaces sliding THEN friction is reduced
p	rolling contact instead of sliding (17)

CS_3:

q	rolling contact instead of sliding
$p \rightarrow q$	IF flexures are used THEN rolling contact replaces sliding
p	flexures (18)

E_3 now comes up with a new problem, of measuring the displacement without friction, so the process continues:

PI_4:

q	displacement measurement without friction
$p \rightarrow q$	IF a noncontact measurement technique is used THEN no friction will be present
p	noncontact measurement technique (19)

CS_4:

q	noncontact measurement technique
$p \rightarrow q$	IF capacitor-type sensor is used THEN a noncontact technique is implemented
p	capacitor-type sensor (20)

Similarly, Example 2 can be presented as the following sequence of pairs of innovative abductions with deductive evaluations between each pair: The first given function, decelerating airborne sensors, led to abducing the concept of flexible parachutes (PI_1), which in turn produced a specific

form (CS_1) by a second abduction. Evaluation showed a potential deployment problem, so its elimination became the next function. The designer now abduced the concept of rigid parachutes (PI_2) and a particular form of such structure (CS_2), but discovered the problem with compact packing. The next cycle of double innovative abductions (PI_3 and CS_3) shows the inference of an "umbrella" concept and the corresponding configuration, followed by deducing that the latest structure was unreliable and expensive. The last PA cycle, comprising PI_4 and CS_4, is a breakthrough in the design process because a totally new concept (spiraling glider) emerged and was realized as a specific hardware description.

7. DISCUSSION

7.1. Reasoning from function to form

Table 1 summarizes the different terms used by the models described in this paper for clarification of their starting point, intermediate entities, and end point. There are four fundamental units involved in the reasoning, for which we may adopt the terms *function, way of use, mode of action, and form*. Some models use other names for these entities, but a bigger difference is in how they are sometimes grouped together, made implicit, or serve a different role.

We propose that reasoning from *function* to *form* may be productively modeled in terms of two creative leaps, each requiring an *abduction-2/innovative abduction* reasoning step. The first infers the solution principle to be used to attain the desired function, and the second infers the artifact that can utilize the solution principle. The pattern of abductions involved is very different from *explanatory abduction* (in the sense

Roozenburg and Habermas have defined the term), so having a special name for this kind of reasoning seems justified.

Solution principle or concept comprises *way of use + mode of action*. The *mode of action* seems to be more fundamental to the reasoning than the *way of use*. *Way of use* may be trivial in many cases, so it may not appear in the description of the inferences. For instance, PI_1 in Example 1 only specifies "a simple pendulum" as the concept (*way of use + mode of action*). However, this is understandable when it comes to designers' reasoning: a simple pendulum implies hanging a weight on a string or rod that is hinged onto some frame (*way of use*), and the *mode of action* is the self-alignment of the pendulum with the gravitational field while the frame is being tilted with the ground, so an angle identical to the ground's inclination is formed between the frame and pendulum. Similarly, decelerating the sensor by a parachute (PI_1 in Example 2) is the obvious *way of use + mode of action* in the overall setting of the design task: it unequivocally means that if the sensor is attached to the parachute with cords and both are released in midair (*way of use*), then drag force due to air resistance will be generated to slow down the fall (*mode of action*). The *way of use* of filling water and putting the water-filled kettle over a burner is also trivial, because the initial problem statement should have involved a burner as the source of thermal energy (and not, for instance, electricity) and the purpose of boiling the water (for making tea, we may want to contain the boiled water, as opposed to producing steam in a sauna).

In contrast to the sometimes hidden presence of the *way of use*, the importance of explicitly including the *mode of action* in the inference cannot be overstated. When the designer thinks in conceptual terms about physical and natural principles, the designed artifact will be based on a solid ideational

Table 1. *Terminology used by the different models*

Model	Starting Point	Intermediate Entities	Final Outcome
Pahl & Beitz' (1984) systematic design	Overall function	Subfunctions, working principles (also physical effects + form)	Principal solution = structure
Gero & Kannengiesser's (2004) function–behavior–structure	Function	Expected behavior, structure (actual) behavior	Structure
Suh's (1990) axiomatic design	Need	Functional requirements	Design parameters = physical solution
Chen et al.'s (2015a, 2015b) need–function–principle system	Function	Abstract principle = action classes + behavior classes	System (structure) with its actions and behaviors
Roozenburg (1993)	Function (also purpose, desired result)	Mode of action (also using laws of nature, functional behavior)	Principal solution = form (also structure) + way of use (also actuation)
Zeng & Cheng (1991)	Function	Environment = laws of nature + actions of nature	Form
Dorst (2011)	(Aspired) value	How (also working principle)	What (also artifact)
Parameter analysis (this paper)	Function	"Parameter" (concept, solution principle, way of use + mode of action)	Configuration

foundation. Alternative principles may be thought of, the rationale of the design will be better captured for possible use in the future, and deeper understanding of the problem domain will be gained by the designer. For instance, the understanding of pendulum physics is what brought about the analogy between a pendulum and a spring (both generate a restoring force proportional and opposite to the displacement (PI_2 in Example 1). Understanding the physics of work (force times distance) is what led to the breakthrough in the decelerators' design, when realizing that vertical descent presumes a distance equal to the release altitude, but this could be modified to spiraling descent. Similarly, the choice of metal construction in the form of the kettle may be modified when explicating the *mode of action*, heating the bottom and conducting the heat to the water inside, perhaps by looking for materials with high thermal diffusivity or combining a heat conducting material for the bottom and a heat insulating material for the sides of the kettle.

Dorst (2011) specifically refers to this issue. When describing the pattern of *abduction-2* as in (11) he says: "students and other novice designers can be seen to almost randomly generate proposals for both the 'how' and the 'what,' and then seek to find a matching pair that does lead to the aspired value." In our experience, the issue is not the random trial-and-error process, but rather an attempt to reason from *function* (aspired *value*) <u>directly</u> to *form* (the *what*), without the intermediate step of reasoning about the *concept* (the *how*).

While the *mode of action* and *way of use* components of the *concept* often seem to co-occur, we can imagine situations where they are separable. The *way of use* may be more dominant in the design of a new mobile phone or other systems in which user experience is of utmost importance. In contrast, new scientific discoveries may render the *mode of action* more central. Innovative design situations may involve knowledge of only one of these components. We may wish to employ the *way of use* of commanding a car by thought alone, but have not yet invented a feasible *mode of action* for doing so. Alternatively, we may wish to utilize the phenomenon of solar pressure for spacecraft propulsion as a *mode of action*, but have yet to develop a practical *way of use* for it.

Whether *mode of action* and *way of use* are conflated or separate appears to depend on the design task statement. If it is relatively constrained, as in the provision of the burner in the kettle example, then *mode of action* and *way of use* may well be regarded as a single entity. If the task is more "open," for example, boiling water for a hot drink, then the *mode of action* should be determined first (e.g., conduction of heat from a fire to the water, resistive heating, conversion of electrical energy to microwaves and radiating them onto the water), to be followed by reasoning about an appropriate *way of use* (e.g., using a container to hold the water above the flame, immersing an electrical heating element in the water, or putting the water container inside a radiation chamber).

The possibility of having separable *mode of action* and *way of use* brings about the option of modeling the function-to-form reasoning as a three-step process among four entities:

from *function* to *mode of action*, then from *mode of action* to *way of use*, and finally, from *way of use* to *form*. All three inferences seem to be of the *innovative abduction* type, as long as the task statement and design requirements leave sufficient options open. However, the current paper deals only with the double-abduction model, in which *mode of action* and *way of use* are assumed conflated.

An interesting point with the analogical reasoning in expressions (15) and (16) of Example 1 is that the PI_2 step maps the world of pendulums into the domain of springs, and determines what the solution would look like in that domain. This working principle, or *concept*, is transferred back to the target domain in the CS_2 step, where the *form* is inferred. The PI step in PA has been characterized in the past as including such types of reasoning as reinterpretation and analogy making (Kroll & Koskela, 2016). Abduction has also been associated with analogical reasoning (Minnameier, 2010).

Having proposed a double *innovative abduction/abduction-2* model, we may ask whether *explanatory abduction/abduction-1* exists in design at all. While March and some other scholars seem to refer to only this type of abduction in the context of design, we have shown that generating both a concept (working principle) and an artifact (form) require abductive reasoning with only one fact, the *desired value*, as a given. In both cases, a rule needs to be inferred first, and the premise of the rule immediately follows. The two inferences do not share the same *desired value*: when generating a working principle, the value is the *function*; when generating the form, the value is the *working principle* of the previous step.

However, we can imagine situations where the working principle is taken as a given, resulting in abduction of pattern (3) occurring. These seem to be cases in which the problem situation is so familiar to the designer that the working principle is taken for granted and becomes implicit in the reasoning. For example, a structural engineer who regularly designs apartment buildings may specify an I-section (*form*) for the ceiling-support beam (implied *function* of carrying bending loads) directly, without consciously thinking of the working principle of increasing the section's second moment of area by placing most of the material away from the neutral axis. This type of design is called "Class 3 design" by Brown and Chandrasekaran (1985), referring to the case of having known and well-understood design alternatives, so no new plans are required. Gero (1990) calls such situations "routine design" (as opposed to two other types, "innovative design" and "creative design"), and characterizes their solution as requiring no new variables and no variable values outside their preset ranges.

However, the above argument does not necessarily imply that *innoduction/abduction-2* occurs only in innovative design situations. Pattern (4) of reasoning, in which the "rule" part (be it *concept → function* or *form → concept*) is not considered a given, can take place in two very different circumstances. First, in the more mundane design situations, many

applicable "rules" may exist in the designer's repertoire, and the abductive step is required to select among them. For example, this may apply to the ceiling-support beam case, when the design requirements are slightly changed and the designer recalls *form → concept* rules concerning C-sections and rectangular-tube sections. Magnani (1995) has called this kind of inference, where one selects from a set of known rules, *selective abduction*. Second, in what may be termed "highly innovative design" situations, the "rule" simply does not exist (either in the particular designer's mind or universally) and needs to be "discovered." For example, if the ceiling-support beam is required to also provide an easy or aesthetic connection to glass walls, the designer may invent a new section shape that is different from "standard" or existing shapes. Inference of a new *concept → function* rule seems even more innovative, because it implies discovering a new working principle to satisfy a function. Consider, for example, the first time houses were built out of shipping containers, or the still-futuristic concept of getting to space with an elevator.

7.2. The need for further clarification of abduction in design

Clearly, the present work is not intended to be the definitive and complete treatment of abduction in design. Just as understanding of abduction in philosophy and other areas still evolves, researchers in design have to develop further understanding of this fundamental notion. In doing so, problems originating both from understanding of abduction in science and from the adoption of abduction in design have to be overcome. In general, while especially March's and Roozenburg's treatments of abduction can be considered seminal and have stimulated further research, they leave room for several critical remarks. These are not meant to downplay the value of the early treatments but rather emphasize their generative value.

The central motivation for defining abduction, from Aristotle to Peirce, has been to cover for logical inferences that cannot be classified as either inductions or deductions. However, this demarcation is made challenging by the situation that still it is not at all clear what induction is, as stated by Vickers (2013): "attempting to define induction would be more difficult than rewarding." Further, Vickers contends that there is no comprehensive theory of sound induction, no set of agreed-upon rules that license good or sound inductive inference, nor is there a serious prospect of such a theory. That induction is not a settled concept makes it difficult to gauge what is outside induction and deduction.

However, there is more to abduction than revealed in logical analysis. Already from Peirce onward, abduction has been connected to intuition and creativity. There has been much research on these two phenomena as such, but there seems to have been very little scholarly attention specifically on the creative and/or intuitive aspects of abduction. These connections need to be cultivated and expanded for

added understanding. One question is whether we need to set criteria regarding or at least acknowledge its intuitive and creative character when defining abduction. In recent literature, Hoffman (1999) seems to have moved into this direction. In this context, two further questions arise. Is all creativity in science or design channeled through abductive inferences? Is creative abduction always based on intuition?

With its origin in the scientific method, the main type of abduction has generally been identified as backward (regressive) reasoning, essentially through guessing, from consequences to hypothetical causes (in opposition to induction and deduction). In design, regressive and deductive inferences along means–ends hierarchies are prominent forms of reasoning. However, there are also other mental moves, such as decomposition and composition, as well as transformation (Koskela et al., 2014). Can we recognize cases in these other design moves that are in essential respects similar to abduction, that is, creatively pinpoint a solution candidate or at least the direction to it? This important question is closely related to the call for classification of different types of design abduction, to be presented below.

In discussions on abduction in philosophy of science, there is a fixation to the syllogistic form of abduction, although already Peirce (1994) downplayed syllogism as "the lowest and most rudimentary of all forms of reasoning." Schurz (2008) cogently argues that there exist rather different kinds of abduction patterns; while some of them enjoy a broad discussion in the literature, other important patterns have been neglected. This fixation to the syllogistic form of abduction has been inherited to treatments of design abduction. The far more common way of conceptualizing design as moves along means–ends hierarchies (Hughes, 2009) is rarely analyzed from the perspective of abduction. To the same effect, Niiniluoto (1999) discusses the foundational role geometrical analysis has played as a model of reasoning in science, covering also abductive inferences in that analysis. However, the philosophical discussions on abduction rarely acknowledge this. The same complaint can be presented regarding the literature on design abduction.

The generic juxtaposition of the terms explanatory abduction and innovative abduction, as suggested by Roozenburg (under influence from Habermas), is not the best possible, because in science also innovative abductions target explanation. The terms *selective abduction* and *creative abduction*, suggested by Magnani (1995), are better in this respect, although as Magnani himself concedes through his examples, the borderline between them is fluid.

Although schematic examples are often good for purposes of presentation and demonstration, the advancement of scientific understanding on abduction requires the examination of abduction-like inferences in design as they occur in practice. Perhaps, in this way, a thorough classification, as done by Schurz (2008) for scientific abductions, could be carried out for design abductions. It is interesting that the work of Takeda et al. (2003) has challenged the completeness of Schurz' classification from a design viewpoint. The attempt

of Ullah et al. (2012) to connect the notion of "classical abduction" as in (3) to the C-K theory of design is another example of research endeavoring to interpret abduction from a design viewpoint. They conclude that conceiving a creative ("undecided" relative to existing knowledge) concept is more complex than abduction, being a motivation-driven process. Motivation here consists of a "compelling reason," why a certain concept is pursued, and an "epistemic challenge," seeking new knowledge.

8. CONCLUSION

It has been proposed here to modify the general model of design reasoning from *function* to *form* to the following two-step inference of the innovative abduction type that explicitly includes the *concept*, solution principle, in it:

First step:

q	given: *function*

| $p \rightarrow q$ | first conclusion: IF *concept* THEN *function* |
| p | second conclusion: *concept* | (21) |

Second step:

q	given: *concept*

| $p \rightarrow q$ | first conclusion: IF *form* THEN *concept* |
| p | second conclusion: *form* | (22) |

This double innovative abduction model can enhance our understanding of design reasoning and contribute to design education and developing computational models in design. Dong et al. (2015), for example, seem to have adopted it to analyze the concept selection stage in design. In addition, we showed how the *parameter identification* and *creative synthesis* reasoning steps in the PA conceptual design method correspond to the above two steps. Finally, several needs for further clarification of abduction have been identified and discussed.

REFERENCES

Brown, D.C., & Chandrasekaran, B. (1985). Expert systems for a class of mechanical design activity. In *Knowledge Engineering in Computer-Aided Design* (Gero, J.S., Ed.), pp. 259–282. Amsterdam: Elsevier.

Burks, A.W. (1946). Peirce's theory of abduction. *Philosophy of Science 13(4)*, 301–306.

Chen, Y., Zhang, Z., Xie, Y., & Zhao, M. (2015a). A new model of conceptual design based on scientific ontology and intentionality theory: Part I. The conceptual foundation. *Design Studies 37*, 12–36.

Chen, Y., Zhao, M., Xie, Y., & Zhang, Z. (2015b). A new model of conceptual design based on scientific ontology and intentionality theory: Part II. The process model. *Design Studies 38*, 139–160.

Cross, N. (2006). *Designerly Ways of Knowing*. London: Springer.

Dew, N. (2007). Abduction: a pre-condition for the intelligent design of strategy. *Journal of Business Strategy 28(4)*, 38–45.

Dong, A., Lovallo, D., & Mounarath, R. (2015). The effect of abductive reasoning on concept selection decisions. *Design Studies 37*, 37–58.

Dorst, K. (2011). The core of "design thinking" and its application. *Design Studies 32(6)*, 521–532.

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

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

Goel, V. (1988). Complicating the "logic of design." *Design Studies 9(4)*, 229–234.

Habermas, J. (1978). *Knowledge and Human Interests*, 2nd ed. London: Heinemann.

Hatchuel, A., & Weil, B. (2009). C-K theory: an advanced formulation. *Research in Engineering Design 19(4)*, 181–192.

Hoffman, M. (1999). Problems with Peirce's concept of abduction. *Foundations of Science 4(3)*, 271–305.

Hughes, J. (2009). Practical reasoning and engineering. In *Philosophy of Technology and Engineering Sciences* (Meijers, A., Ed.), pp. 375–402. Amsterdam: Elsevier.

Koskela, L., Codinhoto, R., Tzortzopoulos, P., & Kagioglou, M. (2014). The Aristotelian proto-theory of design. In *An Anthology of Theories and Models of Design* (Chakrabarti, A., & Blessing, L., Eds.). London: Springer.

Kroll, E. (2013). Design theory and conceptual design: contrasting functional decomposition and morphology with parameter analysis. *Research in Engineering Design 24(2)*, 165–183.

Kroll, E., Condoor, S.S., & Jansson, D.G. (2001). *Innovative Conceptual Design: Theory and Application of Parameter Analysis*. Cambridge: Cambridge University Press.

Kroll, E., & Koskela, L. (2016). Applying the proto-theory of design to explain and modify the parameter analysis method of conceptual design. *International Journal of Design Creativity and Innovation 4(1)*, 1–25. doi:10.1080/21650349.1013568.

Kroll, E., Le Masson, P., & Weil, B. (2014). Steepest-first exploration with learning-based path evaluation: uncovering the design strategy of parameter analysis with C-K theory. *Research in Engineering Design 25(4)*, 351–373.

Li, Y.T., Jansson, D.G., & Cravalho, E.G. (1980). *Technological Innovation in Education and Industry*. New York: Van Nostrand Reinhold.

Magnani, L. (1995). Creative processes in scientific discovery. *European Journal for High Ability 6(2)*, 160–169.

March, L. (1976). The logic of design and the question of value. In *The Architecture of Form* (March, L., Ed.), pp. 1–40. Cambridge: Cambridge University Press.

Minnameier, G. (2010). Abduction, induction, and analogy—on the compound character of analogical inferences. In *Model-Based Reasoning in Science and Technology: Abduction, Logic, and Computational Discovery* (Carnielli, W., Magnani, L., & Pizzi, C., Eds.), pp. 107–119. Berlin: Springer.

Niiniluoto, I. (1999). Defending abduction. *Philosophy of Science 66*, S436–S451.

Otto, K., & Wood, K. (2000). *Product Design: Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ: Prentice–Hall.

Pahl, G., & Beitz, W. (1984). *Engineering Design: A Systematic Approach*, 1st English ed. London: Design Council.

Pauwels, P., De Meyer, R., & Van Campenhout, J. (2013). Design thinking support: information systems versus reasoning. *Design Issues 29(2)*, 42–59.

Peirce, C.S. (1994). *Collected Papers of Charles Sanders Peirce: Vol.* 7. *Science and Philosophy*. Cambridge, MA: Harvard University Press.

Roozenburg, N.F.M. (1993). On the pattern of reasoning in innovative design. *Design Studies 14(1)*, 4–18.

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

Schön, D.A. (1983). *The Reflective Practitioner: How Professionals Think in Action*. New York: Basic Books.

Schurz, G. (2008). Patterns of abduction. *Synthese 164(2)*, 201–234.

Suh, N.P. (1990). *The Principles of Design*. New York: Oxford University Press.

Takeda, H. (1994). Abduction for design. In *Formal Design Methods for CAD* (Gero, J.S., & Tyugu, E., Eds.), pp. 221–244. Amsterdam: North-Holland.

Takeda, H., Sasaki, H., Nomaguchi, Y., Yoshioka, M., Shimomura, Y., & Tomiyama, T. (2003). Universal abduction studio—proposal of a design support environment for creative thinking in design. *Proc. Int. Conf. Engineering Design, ICED'03*. Stockholm: Design Society.

Takeda, H., Veerkamp, P., Tomiyama, T., & Yoshikawa, H. (1990). Modeling design processes. *AI Magazine 11(4)*, 37–48.

Tomiyama, T., Takeda, H., Yoshioka, M., & Shimomura, Y. (2003). Abduction for creative design. *Proc. ASME 2003 Int. Design Engineering Technical Conf., DETC'03*, pp. 543–552, Chicago, September 2–6.

Ullah, A.M.M.S., Rashid, M.M., & Tamaki, J. (2012). On some unique features of C-K theory of design. *CIRP Journal of Manufacturing Science and Technology 5(1)*, 55–66.

Ullman, D.G. (1992). *The Mechanical Design Process*. New York: McGraw–Hill.

Ulrich, K., & Eppinger, S. (2007). *Product Design and Development*, 4th ed. Boston: McGraw–Hill.

Vickers, J. (2013). The problem of induction. In *The Stanford Encyclopedia of Philosophy* (Zalta, E.N., Ed.). Accessed at http://plato.stanford.edu/archives/spr2013/entries/induction-problem/

Zeng, Y., & Cheng, G.D. (1991). On the logic of design. *Design Studies 12(3)*, 137–141.

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