On Abduction in Design

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The mechanism of design reasoning from function to form is addressed by examining the possibility of explaining it as abduction. We propose a new interpretation to some definitions of innovative abduction, to show first that the concept, idea, as the basis for solution must be present in the inference, and second, that the reasoning from function to form is best modeled as a two-step inference, both of the innovative abduction pattern. This double-abductive reasoning is shown also to be the main form of reasoning in the empirically-derived "parameter analysis" method of conceptual design. Finally, the introduction of abduction into design theory is critically assessed, and in so doing, topics for future research are suggested.

Aim

Better understanding of the reasoning mechanism from function to form is the main aim of the current investigation. In previous work [1] we studied the method of parameter analysis (PA) from the perspective of the proto-theory 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 logic-based framework and were characterized as being compositional or transformational/interpretational. Regressive and transformational inferences were of particular interest as they involved heuristic reasoning and intuition, notions that are sometimes associated with the type of inference called abduction. For example, abductive reasoning has been identified with the notions of intuition ([2], p. 33), creativity and subconscious activities [3]. Of course, abduction has for long been discussed in philosophy of science.

The structure of the current paper is therefore as follows. After a brief discussion of how the core of all design processes—reasoning from function to form—is treated in some of the design literature, the notion of abduction in science and design is introduced. Then we examine two papers that seem central in this area, by Roozenburg [4] and Dorst [5]. Roozenburg's ideas on innovative abduction are presented and analyzed both theoretically and through his kettle design example. Next we study Dorst's model of abduction and apply it to the same example. We propose a modification of both Roozenburg's and Dorst's models and relate it back to PA. The paper concludes with critical overall assessment of the introduction of the concept of abduction into design theory, and in so doing makes some suggestions for future research.

The paper intentionally looks at the "mechanics" of the reasoning involved in creating design solutions in terms of the relevant patterns of inference and what are the constituent entities in each inference. The important cognitive issues of what drives the inference and where ideas come from are briefly touched but not systematically investigated. In addition, the activity of evaluating proposed solutions is also left out, as its nature is very different from the so-called "synthetic" activity of generating something new.

How does form follow function?

The design principle of form follows function is widely accepted. But how is form inferred from function? Ullman ([6], p. 140) suggests that this is done by a double mapping process: first from function to concept, and then from concept to form. Many interpretations of this sequence are possible. The German-school systematic design (e.g., [7]) and variations on this approach that appear in many design textbooks (including Ullman's) prescribe 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), and finally, detailing the form (layout) of the concept in the so-called "embodiment design" stage. 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 [4].

Suh's axiomatic design framework consists of the functional space and the physical space [8]. The former contains functional requirements (FRs) and the latter, design parameters (DPs). Mapping FRs into DPs is the core of the design process; but because there can be many mapping techniques, 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.

Another framework, function-behavior-structure or FBS [9], 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). However, this descriptive model does not use the notion of 'concept', in the sense of underlying solution ideas, as an explicit constituent of the design space.

Parameter analysis, PA [10, 11] models the design process differently: it uses function, concept (idea) and form as entities of Ullman's double mapping but at a "smaller scale". Instead of corresponding to whole stages of the design process, PA's prescription consists of repeatedly moving between concept space and configuration space, using three distinct activities that are repeated many times (Figure 1), and in this sense it is similar to the FBS model. The first step, *parameter identification* (PI), corresponds to finding a "parameter" (concept, idea) for resolving a functional issue with the evolving design. This concept is mapped into form by the *creative synthesis* (CS) step, and the last 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 a satisfactory solution has been reached.

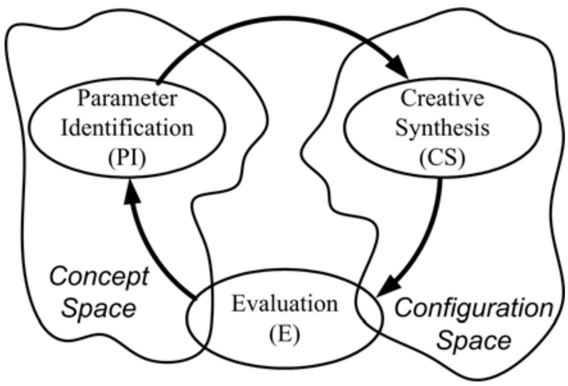

Fig1. The parameter analysis process consists of repeatedly moving between concept space and configuration space by applying parameter identification (PI), creative synthesis (CS) and evaluation (E)

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, etc.—have to be stated explicitly. The E step is considered second in importance, 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, as intermediate configurations are needed mostly to facilitate the evaluation, and any unsatisfactory characteristic of a configuration will be mended in the next cycle. So, 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.

The following examples, although being just fragments of long conceptual design processes, demonstrate the nature of reasoning in PA:

<u>Example 1, from [1]</u>

Deceleration of airborne sensors, dispensed in large numbers from an aircraft for measuring air properties in the airspace over an area, was needed. Three consecutive PA cycles (rephrased for clarity and omitting calculations and sketches for brevity) were:

PI: Produce a large drag force by using the technology of flexible parachutes.
CS: A 150-mm dia. canopy made of thin sheet material and cords to suspend the sensor.
E: The canopy may not open because the "pull" is too weak and cords may tangle.

PI: Overcome the mid-air opening and cord tangling problems by using a rigid parachute.
CS: A 150x150-mm square base pyramid with the sensor attached to it rigidly.
E: Compact packaging of the devices is impossible.

PI: Allow compact packaging by using an umbrella-like folding structure.
CS: Lightweight skeleton with hinges, slides and spring, and thin sheet canopy stretched over it.
E: Unreliable because of the many moving parts and costly to make.

Each PI step contains a function to be satisfied and a concept, solution principle, to do that. The function in the first cycle originated from analyzing the design task, but consecutive functions emerge as a result of previous evaluations. The PI step therefore represents a reasoning step from *function* to *concept*. CS generates a description of a configuration that realizes the last concept, which is *form* of course, and E derives the behavior of the configuration and points the functional direction for the next PI.

Example 2, from [11]
The design process of a sensitive tiltmeter [12] for measuring changes of the ground angle with respect to the local gravity vector was described. A novel configuration emerged, with one regular pendulum coupled mechanically to an inverted pendulum. At this point the configuration was evaluated and the process continued as follows:

E: Friction in the rotational joints must be reduced to ensure the required sensitivity.

PI: Minimize friction by using rolling contact instead of sliding.
CS: Flexural hinges of the appropriate design with near-zero resistance.
E: The displacement measurement should also be made without friction.

PI: Minimize friction by using a non-contact sensing technology.
CS: A capacitor-type sensor.

The first E step above is taken from the middle of the design process, where a new functional issue has come up. Reasoning from this *function* to a *concept* follows in PI and from the *concept* to *form*, in CS. Evaluation of the last configuration reveals a new problem, so another design cycle begins.

A brief introduction to abduction in design

An ongoing debate exists in the philosophy of science and other areas regarding the nature of abductive reasoning. Peirce [13] 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 [14] and certainly on abduction. Schurz [15] presents a thorough classification of abduction patterns, all of which are “special patterns of inference to the best explanation”. He identifies many types of abduction 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
-- (1)
Abduced Conjecture: Ca could be the reason

Investigations of abduction in relation to design have mostly been carried out by scholars in design theory and artificial intelligence. Both streams of research are briefly outlined in the following.

In design theory, March [16] 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: from certain characteristics that are sought, and on the basis of previous knowledge and models of possibilities, a design proposal is put forward.

Roozenburg [4] discusses in depth the question whether the reasoning towards 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 artificial intelligence 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" [17]. In fact, says Roozenburg [4], Habermas distinguished 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 [5] 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'.

In artificial intelligence 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 [18] proposes to extend (and complicate) 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; for example, universal or statistical, and this affects the meaning of the abduction pattern. However, the influential work led by Takeda et al. [19] on design abduction is based on original insights into design, and the connection to Peirce's seminal work on abduction in science seems looser. Abduction is defined as a process making integrated hypotheses and theories to explain given facts [20]. This definition goes beyond Schurz' classification of abduction [21]. Analogical reasoning is applied for computationally supporting abduction [22].

Alone due to space reasons, the focus of this paper is on the design theory oriented research on abduction. However, the artificial intelligence oriented abduction research is touched in the concluding section on future research needs.

Analysis of Roozenburg's model of innovative abduction

Roozenburg [4] says that *explanatory abduction*, also called *presumption of fact*, which seems to him as the prevailing view on abduction, is a reversal of deduction, and <u>is not</u> the main reasoning mechanism in design. Deduction is:

$p \rightarrow q$ (a given rule, IF p THEN q)
p (p is a given fact, a case or cause)
--- (2)
q (q is the conclusion, the result)

Reversing it, we get the following pattern:

$p \rightarrow q$ (a given rule, IF p THEN q)
q (q is a given fact, a result)
--- (3)
p (p is the conclusion, the case or cause)

This is the definition of explanatory abduction, similar to (1). According to Roozenburg, pattern (3) is not the main reasoning form in design, where in fact 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) (4)
p (p is the conclusion, the cause, that immediately follows)

Pattern (4) is the real abduction in design because it represents reasoning from a desired result, a purpose or function, 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.

Roozenburg demonstrates the above through the following example of designing a 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:

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

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:

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

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). But a description of *form* is not enough to predict the behavior which fulfills the *function*. The behavior (*mode of action*) depends on *form* but also on the *way of use*. So, 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) (7)

p hemisphere and metal + fill water and place on burner (*form* + *way of use*; the second conclusion)

The meaning of the last logical derivation 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.

Critique of Roozenburg's model

The question regarding Roozenburg's presentation 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 the specific *mode of action*, which is the main characteristic of the principal solution, and now proceeds according to pattern (7). In other words, we could modify Roozenburg's presentation of abduction to the following (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) (8)

p hemisphere and metal + fill water and place on burner (the second conclusion)

But this raises two new questions: (a) 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 (b) does pattern (8) represent what really happens during design?

To answer these questions, let us try to imagine the thought process while designing a 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 *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 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 the fact that two distinct inferences are carried out:

1st 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* $\rightarrow$ *function*)	(9)
p	fill water and place on burner so heat is conducted to water (the second conclusion: *way of use* + *mode of action*)	

2nd 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*)	(10)
p	hemisphere with opening and metal (the second conclusion: *form*)	

To summarize, the above two-step reasoning allows inferring from *function* to an idea, concept or solution principle (showing 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 two entities, *p* and *q*, but design reasoning should involve four entities: *function, mode of action, way of use,* and *form*. And although we claim that *mode of action* and *way of use* seem to frequently show together, so they can be counted as one entity, the three remaining entities still require two inferences, not one. What Roozenburg did is actually leaving out *mode of action* and grouping *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 [19], which Roozenburg claims arrived at similar 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.

Analysis of Dorst's model of double abduction

Dorst [5] explains 'design thinking' as double abduction, assisted by 'frame creation', which itself is facilitated by 'theme exploration'. His presentation of abduction revolves around the following logical expression:

$$\textit{what} \text{ (the artifact)} + \textit{how} \text{ (the working principle)} \rightarrow \textit{value} \text{ (aspired)} \tag{11}$$

in which the (aspired) *value* is always given. If the *how* is also given, we generate 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 we have a more 'open' problem in which we need 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), which is a "general implication that by applying a certain working principle we will create a specific value". Interestingly, Dorst characterizes the framing activity as being "a form of induction", because it is reasoning back from consequences (this is in conflict with Peirce to whom that kind of reasoning represents abduction). With the help of framing, *abduction-2* takes place according to the following pattern:

$$\begin{array}{ll} q & (q \text{ is the given desired } \textit{value}) \\ \hline p \rightarrow q & (\text{IF } \textit{how} \text{ THEN } \textit{value}\text{, the first conclusion}) \\ p & (\textit{how}\text{, the second conclusion}) \end{array} \tag{12}$$

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.

Critique of Dorst's model

Let us now apply Dorst's double-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". So 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 case here. The *what* is still unknown, 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, and using it as the given to seek a "rule" to tie together a *what* (*form*) to this *how* (working principle), and therefore inferring that *what*. The resulting inference is identical to expression (10).

The double innovative abduction in parameter analysis

Having modified Roozenburg's and Dorst's models of reasoning from *function* to *form* to two *innovative abduction* (or *abduction-2*) inferences, as in (9) and (10), allows us to compare 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 earlier can easily be presented as such double abductions. For instance, the first cycle of Example 1 will be:

<u>1st step, PI:</u>

q	produce a large drag force (the *function*)	
--		
$p \rightarrow q$	IF the sensor is suspended by cords from a flexible parachute THEN a large drag force will be produced (the first conclusion: *way of use* + *mode of action* → *function*)	(13)
p	suspend the sensor by cords from a flexible parachute (the second conclusion: *way of use* + *mode of action*)	

2nd step, CS:

q suspend the sensor by cords from a flexible parachute (the newly generated *way of use* + *mode of action* is now the given)

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p → *q* IF a 150-mm dia. canopy made of thin sheet material and cords THEN the sensor will be suspended from a flexible parachute (the first conclusion: *form* → *way of use* + *mode of action)* (14)

p a 150-mm dia. canopy made of thin sheet material and cords (the second conclusion: *form*)

Conversely, we can formulate the double abduction of the kettle example, expressions (9) and (10) as PA:

PI: Boil water by filling water in a container and placing it on a burner so the heat is conducted to the water.
CS: Hemisphere with opening and made of metal.
E: ...

Discussion

Reasoning from *function* to *form* may be productively modelled in terms of two creative leaps, each requiring an *abduction-2/innovative abduction* reasoning step. The first infers the working principle to be used to attain the desired function, and the second infers the artifact that can utilize the working principle. The pattern of abductions involved is very different from *explanatory abduction*, so having a special name for this kind of reasoning seems justified.

Working principle or concept comprises of *way of use* + *mode of action*. The *mode of action* is much more fundamental to the reasoning than the *way of use*. In fact, *way of use* may be trivial in many cases, so it may not appear in the description of the inferences. Deployment of the sensor suspended from the parachute in Example 1 and letting them both descend slowly is the obvious *way of use* in the overall setting of the design task. 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).

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 working principles, the designed artifact will be based on a solid ideational foundation. Alternative working principles may be thought of, the rationale of the design will be captured better for possible use in the future, and deeper understanding of the problem domain will be gained by the designer. For example, the choice of metal construction in the form of the kettle may be modified according to the *mode of action* of 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 [5] 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*) directly to *form* (the *what*), without the intermediate step of reasoning about the *concept* (the *how*).

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 researchers seem to refer to only this type of abduction in the context of design, we have shown that both generating 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.

But the above argument does not necessarily imply that *innoduction/abduction-2* occur 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 in fact take place in two very different circumstances. First, in the more routine 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 also C-sections and rectangular-tube sections. Magnani [24] has called this kind of inference, where one selects from a set of known rules, *selective abduction*. Second, in what may be termed "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, as 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.

As a conclusion, we propose 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*, working principle, in it:

<u>1st step:</u>

q	given: *function*	
--		
$p \rightarrow q$	first conclusion: IF *concept* THEN *function*	(15)
p	second conclusion: *concept*	

<u>2nd step:</u>

q	given: *concept*	
--		
$p \rightarrow q$	first conclusion: IF *form* THEN *concept*	(16)
p	second conclusion: *form*	

Additionally, we showed how the *parameter identification* and *creative synthesis* reasoning steps in the conceptual design method called "parameter analysis" correspond to the above two steps.

Critical assessment and the way forward

Clearly, this 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' 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 the generative value of them.

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 [14]: "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 indeed difficult to gauge what is outside induction and deduction.

However, there is more to abduction than revealed in logical analysis. Already from Peirce onwards, 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. Indeed 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 [25] 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 backwards (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 [26]. 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 [13] downplayed syllogism as “the lowest and most rudimentary of all forms of reasoning”. Schurz [15] 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 [27] is rarely analyzed from the perspective of abduction. To the same effect, Niiniluoto [28] 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, as in science all abductions target explanation. The terms *selective abduction* and *creative abduction,* suggested by Magnani [24], are better in this respect, although as Magnani himself concedes through his examples, the borderline between these is fluid.

Roozenburg, and also we in this paper, use the hypothetical example of design of a metal kettle in the imagined situation that the world would be otherwise as it is now but the kettle would never have been invented. This raises the question how kettles have actually been designed? Before metal kettles, ceramic kettles were used [29], thus metal kettles probably have emerged just through switching over to metal as material. 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 [15] for scientific abductions, could be carried out for design abductions. Interestingly, already the work of Takeda et al. [22] has challenged the completeness of Schurz’ classification from a design viewpoint. The attempt of Ullah et al. [30] 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.

Finally, as discussed above, design abduction research falls into two main fields, design theory and artificial intelligence. While these two literatures are partially overlapping, there seems to be room for greater mutual awareness as well as for better synthesis of results.

The multitude of problems related to abduction in general and specifically to design abduction may initially seem overwhelming. However, they all give direction for future research, relevant for the advancement of the field.

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