SAPPhIRE: A Multistep Representation for Abductive Reasoning in Design Synthesis

Conference Paper · December 2020

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SAPPhIRE: A Multistep Representation for Abductive Reasoning in Design Synthesis

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Literature suggests that people typically understand knowledge by induction and produce knowledge by synthesis. This paper revisits abduction, a mode of reasoning that has been explored by several researchers as a crucial mode of reasoning underlying design synthesis. Our paper expands earlier work on abduction by proposing a more de-tailed model for abduction based on the seven elementary constructs of the SAPPhIRE model of causality. We argue that this model pro-vides a more comprehensive understanding of abductive reasoning than those proposed by earlier authors. Explanations of abduction in design using the proposed model of abductive reasoning has been compared with those using existing models of abduction; the comparisons indicate the proposed model to be a more extensive model of ab-duction for design synthesis. Further, the model has been used to ex-plain the empirical findings on abduction from the literature, lending further support to the claim to its explanatory capacity.

Aim

"Much of the reasoning in design belongs to the category of plausible reasoning, in particular the reasoning that generates or produces tentative descriptions for solutions to design problems. Which type, or pattern, of plausible inference may be taken as the 'paradigm' model of this crucial step in the design process? This question is important for at least two reasons. Firstly…. And secondly, because both simulating the design process

Design Computing and Cognition DCC'20. J.S. Gero (ed),
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by computers for cognitive reasons and building 'design machines' for practical, technological, purposes involve the modelling of design reasoning in one or the other logical formalism."- Roozenburg [1]

Understanding designing and its underlying reasoning processes have been major areas of research into design. Innovative abductive reasoning is a key mode of reasoning in design where parsimonious explanations are formed from observations [2]. As discussed later in this paper, various authors have investigated the nature of design and the role of abductive reasoning in design. Examples include Roozenburg's single step model and Kroll & Koskela's two-step model of abduction. In this paper, we present another model, which we argue to be more suitable for the analysis of abductive reasoning in design. The model is based upon the SAPPhIRE - a causality model [3]. The proposed model helps to more fully delineate the constructs of design into the elementary constructs for abductive reasoning, thereby providing a more detailed explanation of abduction. The model has been validated by comparing explanations of the same example design case using the proposed model and that produced using a representative model from earlier work.

Reasoning

According to Anderson [4], reasoning refers to the mental processes involved in generating and evaluating logical arguments. Reasoning consists of three parameters: 1. "premises", 2. "results" or "conclusions", and 3. "a rule" or "material implication" or "warrant" that allows movement from one point to another in the logical space [5]. Deductive reasoning is a mode of reasoning in which we take the premises as the starting point and reach the conclusion as the end point, when the underlying rule is known. In contrast, in reductive reasoning, we take the conclusion as the starting point and reach the premises as the end point. Induction and abduction are two different forms of reductive reasoning. Out of all forms, deductive and inductive reasoning are seen as the two prominent modes of reasoning in science. Both these modes seek to eliminate (deductive) or reduce (inductive) uncertainty and neither introduces new knowledge [6]. In contrast, abduction is a form of argument that generates new, or extends existing, knowledge [7]. Appositional reasoning and productive reasoning are the interchangeable names for abductive reasoning.

Abductive reasoning in science

In science, abduction is considered as generation of causal hypothesis for an observed phenomenon. Peirce [8] was the first author who defined abductive reasoning, and distinguished it from inductive and deductive reasoning in the area of science (i.e. scientific discovery). Schurz [9] described abductions as special patterns of inference to the best explanation and tried to provide classification of different patterns of abduction. He also differentiated selective abduction from creative abduction. Nowadays, 3application of abduction is not limited to science but also in the area of medical diagnostics and artificial intelligence. In the medical diagnostic process, various models of expert systems (e.g. MYCIN) were constructed where abduction was used as the core reasoning. If it is known that disease 'A' will cause symptom 'b', abduction will try to identify the explanation for 'b', and deduction will forecast that a patient affected by disease 'A' will manifest symptom 'b' [10].

Abductive reasoning in design

March [11] differentiated the goal of science (i.e. to establish general laws) from the goal of design (i.e. realizing a particular outcome). March also argued abduction to be a key mode of reasoning in design. Dorst [12] argued that design cognition relies, in addition to deductive and inductive reasoning that are often used in scientific discoveries, on abductive reasoning. Abductive reasoning allows the designer to approach a problem despite limited information and resources [1]. Under the term abduction, Peirce subsumed two different processes, without clearly distinguishing between these. The two processes are called explanatory abduction and innovative abduction, which are explained by Habermas [13]. Innovative abduction is different from explanatory abduction, as follows. In explanatory abduction, the antecedent/ cause is to be discovered, with known rule and result. In innovative abduction, on the other hand, the rule and cause are both required to be discovered, while only the result is known. Roozenburg [1] explained both types of abduction comprehensively with the help of examples, and explained as to how abduction is different from deduction and induction. Similarly, Dorst explained two key reasoning patterns in design i.e. Abduction-1 in which 'outcome/ value' and 'working principle' are both known; and Abduction-2 in which only 'outcome' is known [12]. Later, Kroll and Koskela [14] proposed a modification of both Roozenburg's and Dorst's models and came up with a two-step or 'double innovative abduction' model, which has been explained in detail later in the paper.

Dong et. al. [15] conducted an experiment and captured innovative abduction used by participants in the design process. By using Roozenburg's and Kroll & Koskela's models, they came up with five different instances of mental simulation for innovative abduction reasoning: Abductive Structure (AS), Abductive Behavior (AB), Abductive Product (AP), Abductive User (AU) and Abductive Context (AC).

Design synthesis and abductive reasoning

Design is a creative activity that involves bringing into being something new and useful that has not existed before [16]. Designers make use of all modes of reasoning while performing design activities. For instance, according to Archer's three phase model of the design process, inductive reasoning and deductive reasoning are required, respectively, during the analytical and the creative phases [17]. Using a study of Parameter Analysis (PA), researchers in [18] identified deductive reasoning in Evaluation (E) step, regressive (transformational/interpretational) reasoning in Parameter Identification (PI) step, and regressive and compositional reasoning in the Creative Synthesis (CS) step. Later, Kroll and Koskela [14] have related regressive and transformational inferences (being involved in heuristic reasoning and intuition) to abduction.

The design cycle also includes the process of synthesis. Synthesis is a part of the conceptual phase of design which leads to provisional solutions for a given design problem. Synthesis is about combining ideas, concepts or solutions into new ideas, concepts or solutions. Synthesis involves reasoning from a statement on purpose (function) of a new artefact to a statement on its form and use (structure) [1]. In contrast, analysis involves reasoning from form to purpose. When we consider any system, the form (structure) of that system can only have one intended purpose (function). That shows the deductive nature of analysis. However, purpose does not determine a unique form. The same purpose can be achieved and realized by different forms [19]. As synthesis is a process of deriving an artefact's form from a given purpose, synthesis has the ability to transform the purpose into many solution forms, each of which can fulfil the given purpose. This shows the abductive nature of synthesis.

Abductive reasoning is needed when a design problem has a clear value to be reached (which is determined by the user or client), but the solution to be generated as well as the working principle to guide the designer to the desired value are unknown [12]. Each abduction may only be a partial resolution of the design problem, the depth of which depends on the complexity of the problem and the number of sub-problems to be resolved [20].

Roozenburg's one step model of innovative abduction

Roozenburg explains that synthesis can be thought of as reasoning from statements on the functions (or intended behavior) to a description of the form (or structure) of the designed object, and this pattern of reasoning is innovative abduction [21]. The one-step model of abduction given by Roozenburg has been represented as follows:

There are four distinct entities involved in the reasoning: *function, mode of action, way of use (actuation),* and *form.* Here, *function* represents *a desired purpose*; *mode of action* represents what the artefact does; *way of use* or *actuation* represents how the artefact should be used and *form* represents what the artefact consists of. Roozenburg grouped *form* and *way of use* into a single entity, claiming that they always go hand in hand, and writes:

form + way of use (actuation) → mode of action → function *... (1)*

The intermediate result (i.e. mode of action) in Expression (1) can be omitted, so what is left is [14]:

form + way of use (actuation) → function *... (2)*

According to Equation (2), if we consider a given function as the result (q), then first we need to find a form (which consists of geometrical and physiochemical properties) + way of use that fulfills the given function, as the primary conclusion (p→q/ rule) and later, form and way of use (p) as the secondary conclusion.

q	*q is a given fact, a desired purpose*
p→q	*a rule to be inferred first, IF p THEN q*
p	*p is the conclusion, i.e. the cause that immediately follows (description of form and prescription of actuation)*

(Source: [14]) ... (3)

Roozenburg explains the concept of abduction by using the example of boiling water as a desired purpose and a kettle as a form for boiling water. Boiling water is the process of transforming water from say 20°C to 100°C (a desired purpose). The bottom of the kettle is heated (which in this case is actuation) and transports the heat to the water by conduction (i.e. mode of action), which raises the temperature of water. One must fill the kettle with water and place it on a burner (i.e. way of use). One must decide the shape, and select the material, of the kettle (i.e. form).

q	*boil water*	*only the function is given*
p→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*

(Source: [14]) … (4)

In the description given by Roozenburg, the mode of action and actuation have been considered implicitly.

Kroll & Koskela's two step model of innovative abduction

Kroll and Koskela [14] came up with a two-step, or double innovative abduction. Based on this, two distinct inferences have been made. The model splits the one step reasoning of the Roozenburg model into two: Step one explains the reasoning from the function to the mode of action + way of use, while Step two explains the reasoning from the mode of action + way of use to the form.

Step 1: way of use + mode of action → function [14]

q	*boil water*	*the function*
p→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*

(Source: [14]) … (5)

Step 2: form → way of use + mode of action [14]

q	*fill water and place on burner so heat is conducted to water*	*the newly generated way of use + mode of action is now given*
p→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*

(Source: [14]) … (6)

To summarize, the above two-step reasoning allows inferring, first, from *function* to an idea, concept or solution principle (shown as *way of use + mode of action*), and then from that principle to the *form*.

(Note: The tea kettle example shown here might be perceived actually less intuitive, as it is already scientifically proven as true. In other words, the example actually shows deductive reasoning as almost all designers know that water can be boiled by heating a kettle. However, the example explained by Roozenburg refers to the design of the first-ever kettle. Thus, in order to understand the reasoning steps, the authors have adopted the same example for the explanation).

SAPPhIRE: An approach to synthesis

A model of causality- SAPPhIRE is an abbreviation of seven elementary constructs: States, Actions, Parts, Phenomena, Inputs, oRgans, and Effects which was proposed in [3]. These seven constructs and relationships among these have been proposed in a model to help understand the behavior of a system at multiple levels of abstraction. SAPPhIRE model allows a richer and finer description of the causal behavior of a system over models such as Function-Behavior-Structure (FBS) framework [32]. If we map SAPPhIRE model to FBS model, we see that the construct 'action' in SAPPhIRE could be taken as 'function' in FBS; 'parts' in SAPPhIRE could be interpreted as 'structure' in FBS; the other constructs of SAPPhIRE work together to generate the 'behavior' in FBS.
The explanatory efficacy of these two models have been compared in earlier work [3, 22]]. The constructs of the SAPPhIRE model have been used in previous work to develop structured representations of natural and artificial systems; and formed the basis of a computational tool called Idea-Inspire [3]. Subsequent versions [23] of Idea-Inspire have been used as a tool for inspiring ideation using a searchable knowledge-base.

A brief description of the seven constructs of SAPPhIRE is provided below [24]:

"1. *Parts:* A set of physical components and interfaces constituting a system and its environment of interaction.

2. *State:* It is a property at an instant of time of a system (and environment), that is involved in an interaction between a system and environment. As a consequence of an interaction, the property of a system (and environment) changes and this is called a state change.

3. *Organ:* A set of properties and conditions of a system and its environment required for an interaction between them. These are also required

for activating the effect and remain constant during an interaction. All the other requirements apart from the input required for activating the effect comprise the organ.

4. *Physical effect:* A principle of the universe that underlies/governs an interaction.

5. *Input:* A physical variable that comes from outside the system boundary which is essential for an interaction between a system and its environment. This quantity can take the form of material, energy or information.

6. *Physical phenomenon:* It refers to an interaction between a system and its environment.

7. *Action:* An abstract description or high-level interpretation of a change of state, a changed state, or creation of an input." [24]

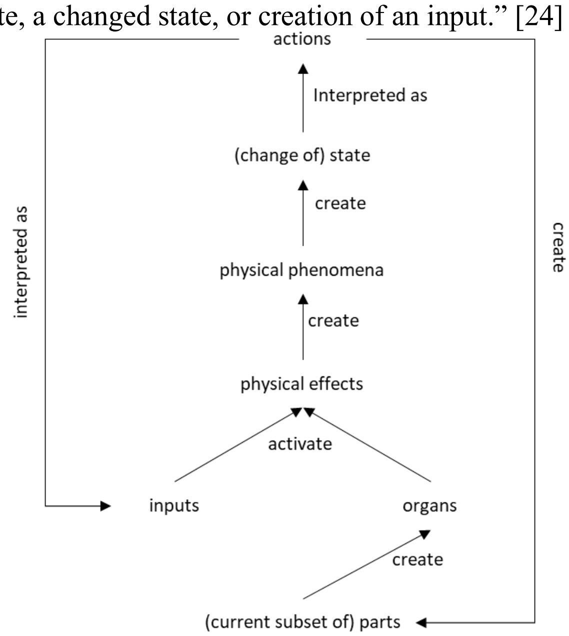

Fig 1. SAPPhIRE model of causality

As shown in Figure 1, a brief explanation of the working of these constructs are given below: parts are necessary for creating organs. Organs and inputs are necessary for activation of physical effects, which in turn is necessary for creating physical phenomena and changes of state; changes of state are interpreted as actions or inputs and create or activate (new) parts [3].

Research published in [24] has reported the application of SAPPhIRE model in describing the synthesis of multi-domain, complex systems across areas such as mechanical, thermal and electrical domains. For the process of synthesis, SAPPhIRE model allows linking of SAPPhIRE constructs (as explained earlier) to create multiple possible outcomes at each level of abstraction, from which a designer can select the most promising ones for further development. Thus, SAPPhIRE model can be used for synthesis in design as discussed by [24].

The SAPPhIRE model was empirically tested to evaluate the extent to which the constructs of the model were present in the design sessions involved. Results showed that each solution exhibited different outcome patterns. Study confirmed that all teams of designers started from the action level construct and ended with part level descriptions. During transition from the action level to the part level, designers passed through one or more intermediate levels of abstractions. The detailed description of the type of patterns are described in the original paper [25].

Comparison of SAPPhIRE model with Roozenburg's and Kroll & Koskela's models

A comparison of SAPPhIRE constructs as explained in the previous section with the corresponding entities of Roozenbug's model is depicted in Table 1. "Organs" and "Parts" constitute "form", "Physical effect" and "phenomena" constitute "mode of action", "State change" and "action" constitute "function" of Roozenburg's model. These constructs of SAPPhIRE act as missing entities and help to encode synthesizing process in greater details.

Table 1 Comparison of SAPPhIRE constructs with the entities of Roozenburg's model

Roozenburg's model		**SAPPhIRE model**	
Construct	**Example**	**Construct**	**Example**
Function	Boil water	Actions	Boil water
		State change	Increasing the quantity of heat in the water
Mode of action	Heat is conducted to water	Physical phenomena	Heat transfer
		Physical effects	Conduction
Way of use	Fill water and place on burner	Inputs	Fill water and place on burner
Form (geometrical and physiochemical properties)	Hemisphere with opening and metal	Organs	Thermal conductivity, thickness, cross-section area
		Parts	Hemisphere with opening

In the given example, Roozenburg considers boiling as the process of bringing water (i.e. transforming water) from 20°C to 100°C. Here, he tacitly took the surrounding pressure as one atmospheric pressure (1 bar). Boiling water is the action here that can be achieved even by changing the pressure alone, which is another way of achieving state change and fulfilling the action of boiling water. The "purpose" in Roozenburg's theory encompasses both action and state change.

Roozenburg then defines mode of action as a behavior of the artefact itself, in response to influences exerted on it from its environment. To raise the temperature of water, he has defined "heat transfer to kettle" as a mode of action. Here, he has tacitly considered the mode of heat transfer as conduction. In reality, however, heat transfer can also be achieved by different effects and modes e.g. radiation. The "mode of action" in his model considers phenomenon and effect together.

Roozenburg defines form as a conjunction of several categorical statements such as: the diameter of the kettle is d, its shape is a hemisphere, it is made from stainless steel, etc. He divides *form* into two parts: 1. Geometrical form and 2. Physicochemical form (the chosen materials). However, in the description he has considered the existence of both parts together while selecting a form. This can be further separated out. i.e. same material (organs) but different geometrical properties (parts).

Roozenburg has considered user-action as an actuation of the artefact. In the example, "filling the kettle with water and placing it on a burner" has been considered as an actuation. Filling the kettle with water and placing the kettle on a burner both are two new actions in themselves and thus contain information more than just giving an input.

Kroll & Koskela's two-step abduction model exhibits similar limitations as explained for Roozenburg's model.

SAPPhIRE: Five step model for abduction

The Five-step model of abduction using SAPPhIRE constructs, as proposed in this paper, is as discussed below.

Here the first step of abductive reasoning generates a rule $p \rightarrow q$ (state change → action) that satisfies a given fact q (action) and based on rule, p (state change) becomes a conclusion. For the next step, the conclusion p (state change) which is inferred in the first step, acts as a fact q in the successive step of abduction; by using fact q, we generate another rule and conclusion. So, the successive innovative abduction can be described by a chain of five interdependent sub steps of innovative abduction.

Step 1: inference to state change

q	*boil water*	*the function (action)*
p→q	*IF increasing the quantity of heat in the water THEN boil water*	*the first conclusion: way of state change → function (action)*
p	*increasing the quantity of heat in the water*	*the second conclusion: way of state change*

... (7)

Step 2: inference to phenomenon

q	*increasing the quantity of heat in the water*	*the newly generated way of state change is now given*
p→q	*IF heat transfer THEN increasing the quantity of heat in the water*	*the first conclusion: type of physical phenomenon → state change*
p	*heat transfer*	*the second conclusion: type of physical phenomenon*

... (8)

Step 3: inference to effect

q	*heat transfer*	*type of physical phenomenon*
p→q	*IF conduction THEN heat transfer*	*the first conclusion: type of physical effect → type of physical phenomenon*
p	*conduction*	*the second conclusion: type of physical effect*

... (9)

Step 4: inference to Organ + input

q	*conduction*	*type of physical effect*
p→q	*IF thermal conductivity, thickness, cross-section area (organ) and fill water and place on burner (input) THEN conduction*	*the first conclusion: type of physical effect → organ +input*
p	*thermal conductivity, thickness, cross- section area (organ) and fill water and place on burner (input)*	*the second conclusion: organ +input*

... (10)

Step 5: inference to Part

q	*thermal conductivity, thickness, cross- section area (organ) and fill water and place on burner (input)*	*organ +input*
p→q	*IF hemisphere with opening THEN thermal conductivity, thickness, cross- section area (organ) and fill water and place on burner (input)*	*the first conclusion: part → organ +input*
p	*hemisphere with opening*	*the second conclusion: part*

... *(11)*

To summarize, the above representation shows the five-step process of abduction. These five-step reasoning allows inferring from action to state change (7), from that state change to phenomenon (8), from phenomenon to effect (9), from effect to organ and input (10) and from organ to parts (11). The above description has been compared with existing two models, the results of which have been depicted in Figure 2. Although the authors of this paper have divided abductive reasoning of design into five steps, in some cases it may involve fewer steps, where some steps combine more than one construct of SAPPhIRE.

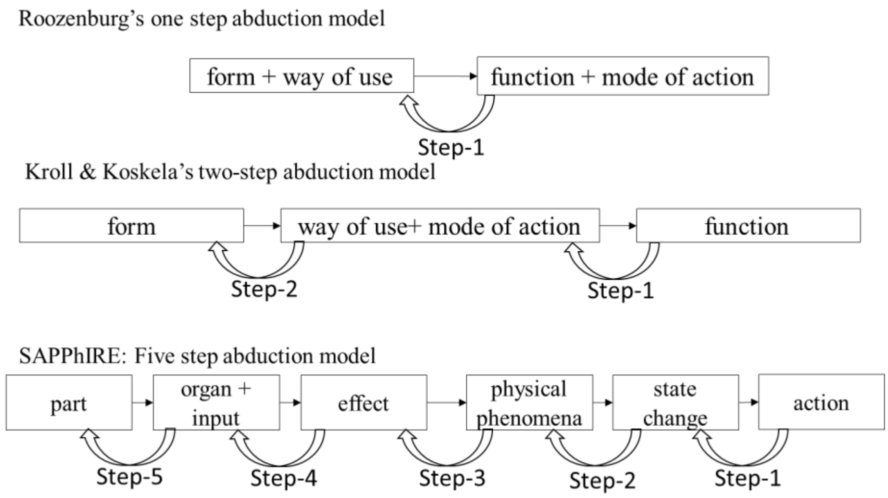

Fig 2 Abduction: comparison of SAPPhIRE model with Roozenburg's and kroll & Koskela's model

We take below a hypothetical scenario of designing in order to illustrate the presence of abduction in the context of the SAPPhIRE framework.

A food making company sells 'ready to eat' meals. Before serving the food, one needs to heat a sealed pouch of food in boiling water, or snip the corner of the pouch and microwave for several seconds. Now, the company wants to develop a solution for inconvenient, adverse, outdoor environment where food can be heated up even if there is no access to microwave oven or stove. In order to solve the above problem, the designer may reason as follows: "I need to heat the food without accessing a stove or microwave oven. Or I can also boil water and then heat the food with the help of boiled water. But as heat transfer is not an option, I could use heat generation. There may a chemical process which exhibits exothermic reaction with water. Therefore, I would look for different chemical exothermic reactions with water."

Here, no access to the use of oven or stove is a constraint, and availability of water is an assumption. With his intuitive insight, the designer is intervening the phenomena first, followed by the effects. This shows presence of abduction at phenomenon and effect level. Using SAPPhIRE constructs, the authors have tried to synthesize all possible ways to achieve boiling of water (depicted in Figure 3).

The requirement of boiling water has been taken as an action. Water can be boiled by alternative state change processes – by reducing pressure, by increasing temperature or by combining both (reducing pressure and increasing temperature). Note that, all of these state changes can be obtained by alternative phenomena. For instance, heat generation, heat transfer or both together can cause rise in temperature etc. Each phenomenon can be achieved by alternative effects. i.e. heat generation can be obtained by chemical reaction (exothermic), mechanical work (friction) or may be by Joule-Thomson effect. Likewise, heat transfer can be obtained by three different modes i.e. conduction, convection or radiation. Each effect requires its own properties and conditions which are described as an organ. For instance, thermal conductivity of a material of body (k), Thickness of body (x), Area of cross section of body (A) can all act as organs for conduction heat transfer. The temperature difference between container and heat source acts as an input. Again, organ can be embodied with different possibilities of part configurations. e.g. kettle is one possible embodiment we can take and proceed further.

Another example to explain the SAPPhIRE model for abduction is illustrated in Figure 4. In this example, the required action is to elevate liquid that can be obtained by various state changes e.g. either changing the phase of the liquid by converting it into its gaseous form, allowing it to move upward and then converting back to the liquid phase; or, inducing or exerting a force on the liquid (phenomena) and changing its height without changing its phase. The force can be induced in the liquid by centrifugal

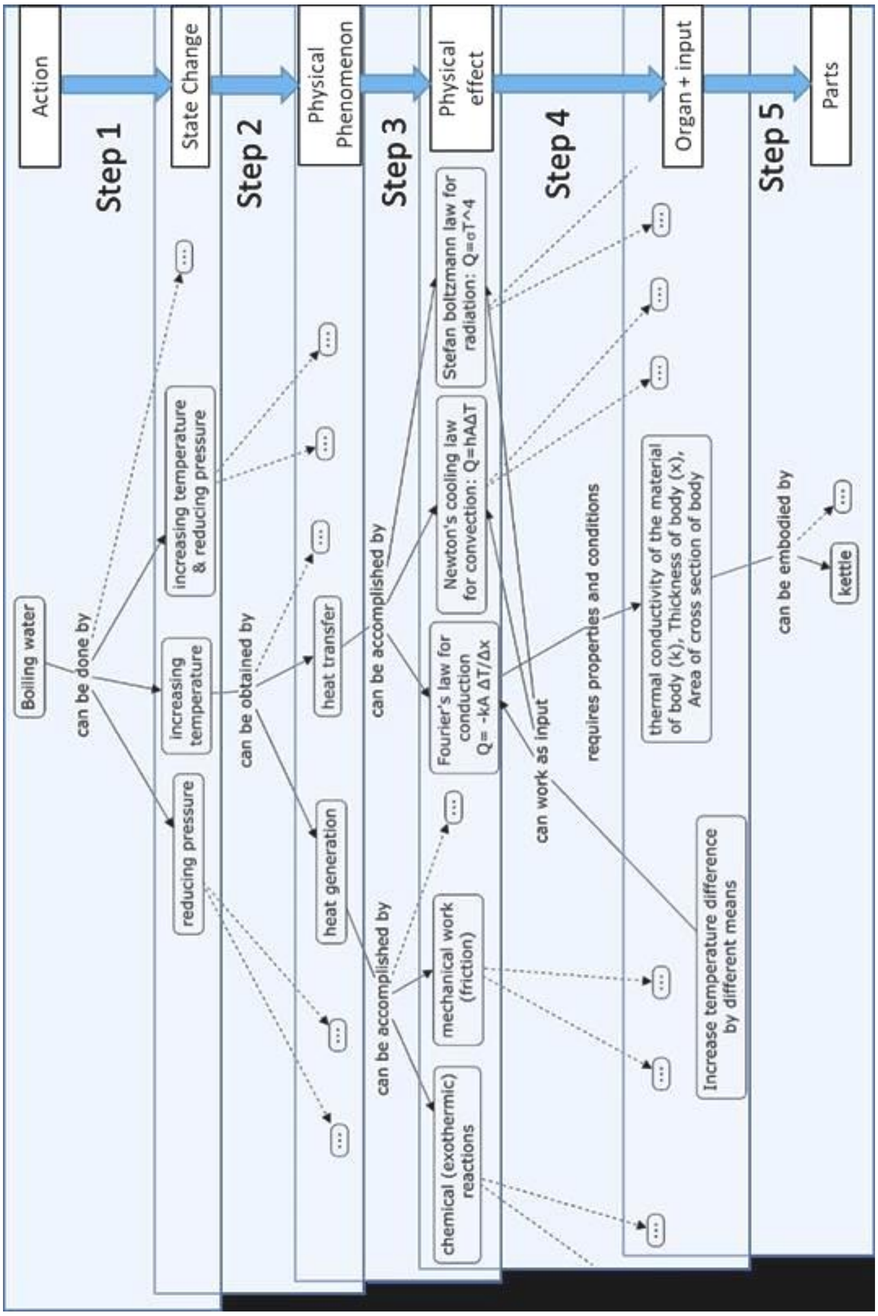

Fig 3. Boiling water illustration, reasoning with SAPPhIRE model

effect, or electromagnetic effect, or some other effect. Similarly, the force can be exerted on the liquid by an impulse or a positive displacement. Each effect requires its own properties and conditions which are described as organs. For instance, impeller diameter and density of liquid are organs for the centrifugal effect, for which the rotational force acts as an input. Again, an organ can be embodied using various, alternative part configurations such as radial pump, axial pump, etc.

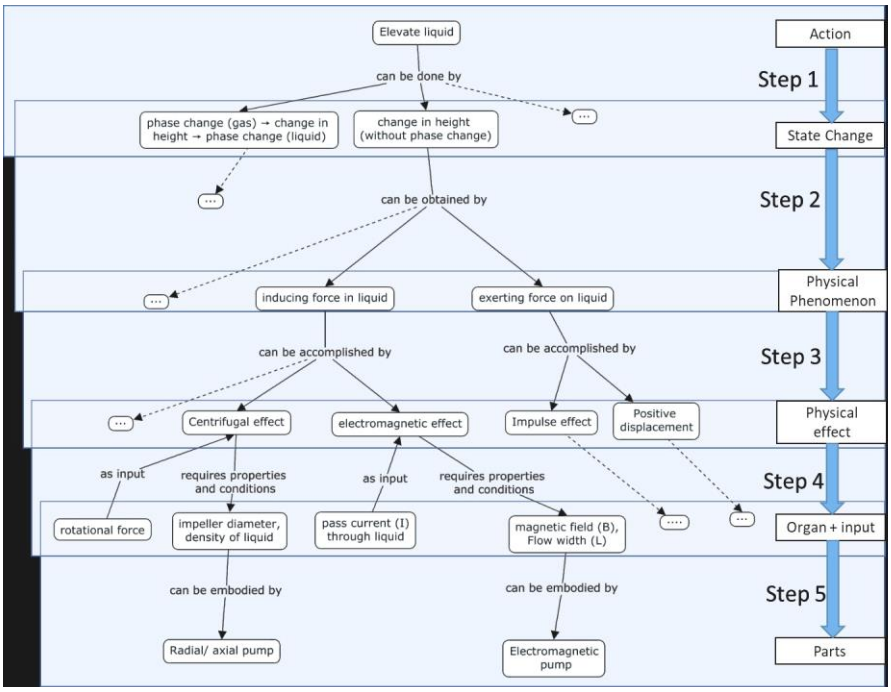

Fig 4. Elevating liquid illustration, reasoning with SAPPhIRE model

In the above examples, the process of synthesis (from action to part) consists of five partial steps of reasoning. The authors argue that each step depicts innovative abduction, selective abduction, or deduction. The interpretation of selective abduction has been clarified by [26]. At each divergent step of design, a designer already knows some alternatives, or generates new alternatives. The activity of using a known solution is related to deductive reasoning. In contrast, the activity of generation is related to abductive reasoning. Though abduction is an essential mode of reasoning for synthesis, it alone is not adequate to explain the whole design process. For instance, after generating the various constructs with the help of the reasoning process proposed in this paper, one may evaluate each of these alternatives against the given criteria (requirements). For instance, although boiling of water can be achieved by reducing pressure that is exerted on water (Step 1), and pressure can be reduced by creating vacuum (Step 2), it may not be the best alternative with respect to economic criteria. Chemical reactions for heat generation (Step 3) can change the constitution of water as an additional effect, which may not be acceptable. Heat generated by Joule-Thompson effect (Step 3) may not be adequate (due to large amount of force required in throttling process) for boiling water (Step 3). Positive displacement pumps (step 3) may not be best for generating higher discharge at low heads. The above examples show that, process of choosing one alternative (that satisfies requirements/ constraint most) from others shows selective abduction.

Conclusion & future directions

The novelty of this paper is in its analysis of the various interpretations of abduction by Roozenburg and Kroll & Koskela, and the proposal that design abduction can be better understood in terms of the SAPPhIRE model. Moreover, abductive reasoning involved in the process of synthesizing can be captured in greater detail with the help of SAPPhIRE constructs. A validation of the model is presented by demonstrating its application in design with two examples. Further, the authors demonstrate that SAPPhIRE model can depict deduction and selective abduction.

In design theory literature, there are many models that prescribed as to how designing should be carried out (e.g. VDI [27], Systematic design [28], Integral design process [29], Integrated model of designing [26] etc.). In recent work, using two different prescriptive design models (i.e. systematic design and parameter analysis) Kroll and Koskela [30] have shown the presence of abductive reasoning.

The authors argue that the extended integrated model of designing [31] can be a more comprehensive way of explaining the various reasoning that occur in design. The model consists of four activities (generate, evaluate, modify and select), seven constructs of SAPPhIRE, two outcomes (requirement and solution), and four system elements. It was developed and validated as a process knowledge support for design for variety and novelty [33]. This descriptive model is grounded in empirical studies of designing, which gives some credence to its potential, explanatory ability. The framework helps explain as to how designers perform activities such as to generate outcomes, to evaluate and to modify those outcomes for the refinement and to select the best among them. These activities can be occurred at various abstraction level of SAPPhIRE constructs where the outcomes can be either solutions or requirements. The overall framework is depicted in figure 5.

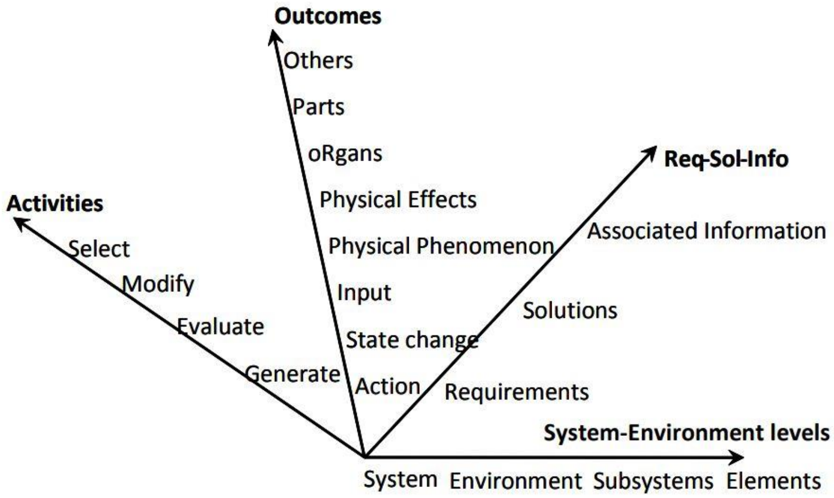

Fig 5. Integrated model of designing: GEMS of SAPPhIRE as Req-Sol [30]

The authors argue that the same framework can help to capture various reasoning presented in activities and make them explicitly available. The various activities involved in the design process and the corresponding types of reasoning involved in each have been represented in Table 2.

Table 2 Reasoning involved in design activities

Activities	Reasoning
Generate	Innovative abduction/ Deduction
Evaluate-Select	Selective abduction
Evaluate-Modify	Deduction-Abduction

Understanding abduction in greater detail should be useful for multiple reasons. The first is the ability to teach design in more detail. The second is to develop tools and methods for supporting abduction. However, before these can be carried out, the steps of the model proposed need to be further grounded on empirical research. The explanation of the findings from Dong et. al. [15] is a single case; more such studies need to be carried out to validate and refine the model. This is part of future work.

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