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Abductive reasoning for design synthesis

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ABSTRACT

Abductive reasoning as a type of "intelligent guessing" has significant impacts on design synthesis. This is particularly evident at early design stages when synthesis must be carried out with only intangible intents and incomplete information. This paper elaborates three types of applicability of abductive reasoning for design synthesis including: identification of implicit design targets, ideation of innovative design concepts, and diagnosis of violating design constraints or design axioms. These studies are then combined to develop a synthesis reasoning process in order to support early-stage design. Some real-world examples are used to illustrate the potential applications in design practice.

1. Introduction

Abductive reasoning is a type of logical inference described by Peirce as "intelligent guessing" [1]. It refers to the process of arriving at a hypothesis to explain a given observation or to achieve a desired consequence. Abductive reasoning is considered critical to engineering design in general and design synthesis in particular [2]. As a special type of abductive reasoning, design synthesis "leaps" from an abstract design intent to a concrete design concept. This task is especially difficult at early design stages when synthesis must be carried out with only intangible intents, incomplete information and uncertain design knowledge. In addition, because abductive reasoning can create new design knowledge [1], it is also closely related to the innovativeness of synthesis results in design.

Abductive reasoning is not foreign to the engineering community. Many of its applications can be found in Artificial Intelligence, where abduction is generally interpreted as the "backward deduction with additional conditions" [3]. Based on such understanding, abductive reasoning shows unique values to many automation tasks such as logic programming [4], diagnosis [5], and planning [6]. Nevertheless, few research efforts have been devoted to investigate the "forward creation with mental leap" capability of abductive reasoning for design synthesis. Most existing works that attempt to associate abductive reasoning with design synthesis only rely on the computational aspects of abductive reasoning to model design synthesis as a logical and computational process [7,8]. Those models, although useful in certain scenarios, do not explicitly indicate the hidden correlations between abductive reasoning and design synthesis. Hence, they are not sufficient to guide designers' mental reasoning in a more systematic and rational manner.

This paper elaborates three types of applicability of abductive reasoning for design synthesis. Based on these studies, we introduce an abduction-based synthesis reasoning process which can guide designers to systemically synthesize intangible design intents, general design axioms, incomplete design information, and applicable design knowledge to generate and select good design concepts at early stages of design. An illustrative example is provided to demonstrate potential applications of the proposed synthesis reasoning process in design practice.

2. Applicability of abductive reasoning for design synthesis

2.1. Characteristics of abductive reasoning

Abductive reasoning has several distinguishing features that are particularly relevant to design synthesis. Firstly, the result of abductive reasoning is a hypothesis. For Peirce, the original purpose of introducing the notion of abductive reasoning was to support the "guessing" process (i.e., how to generate a hypothesis) in a systemic manner [1]. Secondly, according to Peirce's classification of reasoning, abduction belongs to the synthetic reasoning that can extend and add new knowledge [1]. Thirdly, abductive reasoning does not guarantee a uniquely true answer; it can lead to multiple possibilities. Even if the truth of the input of abduction is granted, the result of reasoning might still be false and subject to further validation and improvement. Fourthly, abductive reasoning involves both hypothesis generation and hypothesis evaluation [3]. Peirce suggests two criteria, namely "clarity" and "simplicity" [1], to select the "good" hypothesis. Finally, abductive reasoning can be further classified into different patterns. According to Schurz's classification [9], there are three types of creative abductions, namely factual abduction, law-abduction, and second-order existential abduction.

2.2. Logic foundation of synthesis reasoning

From a theoretical viewpoint, synthesis means a purposeful reasoning from the general to the particular [10]. From a practical viewpoint, synthesis in design can be viewed as repeatedly making purposeful propositions (i.e., subject-predicate pairs) to map from

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the ENDS (i.e., what) to the MEANS (i.e., how) under constraints [11]. It suggests that the central task behind design synthesis is to propose some possible "how" entity in order to realize the given "what" entity. As mentioned in Section 2.1, "to propose something new" is exactly the kind of issue abductive reasoning attempts to address. If design synthesis is approached from the above two perspectives at the same time, it can be modelled as a purposeful abductive reasoning activity from an abstract design intent (i.e., what) to a concrete design concept (i.e., how) under constraints [11]. It means that designers employ the general design intent (which is treated as the desired consequence) and background design knowledge to abductively reason (to guess or propose) for the particular design concept (which is treated as the possible precondition).

In addition to abductive reasoning, deductive reasoning and inductive reasoning also play important roles in design. Deductive reasoning can be used to derive design specifications and stimulate design performance based on chosen design concepts and already known design knowledge. Hence, deductive reasoning is viewed as the logic foundation of design analysis. In design, inductive reasoning is commonly used to develop general design rules and design axioms. In addition, designers can also employ inductive reasoning to evaluate if the proposed design concept can completely satisfy the initial design intent through experiments. Therefore, inductive reasoning can be viewed as the logic foundation of design evaluation. The iterative loop formed by synthesis, analysis, and evaluation in design matches perfectly with the complete logical inquiry cycle: abduction generates new hypotheses; deduction analyzes the hypotheses; and finally induction justifies the hypothesis [12].

2.3. Application of abductive reasoning to design synthesis

After formulating design synthesis as an abductive reasoning activity in Section 2.2, we will discuss three specific applications of abductive reasoning to different challenges of design synthesis in practice. For each challenge, we prescribe a particular kind of abduction pattern. These applications are summarized in Table 1.

2.3.1. Identification of implicit design targets

Abductive reasoning can be applied to identify implicit design targets. Within design synthesis, design target should be carefully distinguished from design intent. Similar to the difference between strategic goal and tactical objective in planning, for a certain design task, design intent describes the highest overall goal to achieve, whereas design target defines the necessary steps (objectives or milestones) to approach that goal. Hence, design target is always more concrete and detailed than design intent. In Axiomatic Design [13], for example, design intent and design target can be seen as conceptually equivalent to "customer need (CN)" and "functional requirement (FR)" respectively.

In general, various design intents can all be simplified as "to satisfy what customer wants". That is to say that a design intent only draws a desired conclusion (i.e., what), while designers should follow abductive reasoning to "guess" a concrete explanation (i.e., how). Different from design intent, design target can be regarded as either input or output of abductive reasoning. When described as designer's wishlist of certain non-existing (or to-be-instantiated) function/behavior, design target should be treated as the desired consequence (i.e., the input of abductive reasoning) that is to-be-realized by some design concept. However, when regarded as the necessary steps to approach the highest design goal, design targets become the precondition (i.e., the output of abductive reasoning) in achieving the design intent. In summary, both design intent and design target can serve as the initial input of abductive reasoning, but in different level of abstraction. In case of design synthesis, if level of abstraction of the given design intent is relatively high, it is necessary to firstly transform the abstract design intent to more concrete design targets using abductive reasoning.

Second order existential abduction [9,14] is considered to play a key role in combing existing theories to seek for the partially new explanation. Therefore, it can be used to support identification of implicit design target in design synthesis.

2.3.2. Ideation of innovative design concepts

The central task of design synthesis is to propose possible design concepts that can instantiate the initial design intent (or its implied design targets). Previous studies indicate that factual abduction [9] can be used to support such application. Specifically, designers employ first order existential abduction (i.e., one particular type of factual abduction) to generate possible entities that can deliver the desired functions [2]. In factual abduction, both the consequence to be achieved and the hypothesis to be proposed are described as singular fact. Below is an example of using factual abduction to ideate new design concepts:

- Initial design intent: to preserve food.
- Background design knowledge: keeping food at low temperature can preserve food.
- Possible design concepts: refrigerator, freezer, ice, etc.

The ideation of new design concepts can also be supported by law-abduction. In law-abduction, both the desired consequence and the possible hypothesis are expressed as certain laws. The reasoning process is, therefore, completely driven by the choice of background law. Below is an example:

- Initial design intent (empirical law): car must move.
- Applicable design knowledge (background law): all objects with wheels can move.
- Proposed design concept (new law): car should have wheels.

If designers employ law-abduction to ideate new design concepts, the chance of success of the proposed concepts becomes higher, because the entire reasoning process consists of multiple chaining laws. However, the novelty and diversity of ideated concepts are likely to be less. This is due to the fact that laws always contain much more tangible information and rigid frames than singular facts, which will limit designer's ideation.

At early stages, design target/objective (i.e., functional requirement, or FR) plays the transitional role between the initial design intent/goal (i.e., customer need, or CN) and the final design concept/result (i.e., design parameter, or DP). Rather than directly leap from the design problem to the design solution, which is the conventional usage of abduction to design synthesis [15], in this

Table 1
Summary of the applications of abductive reasoning to design synthesis.

Application to design synthesis	Type of abductive reasoning	Desired/given consequence	Applicable rules	Possible explanation (precondition)
Identification of implicit design target (i.e., FR)	Second order existential abduction	Customer needs (CN)	CNs can be satisfied by certain FRs; FR is more concrete than CN	Functional requirements (FR)
Ideation of innovative design concepts (i.e., DP)	Factual abduction or law-abduction	Functional requirements (FR)	FR can be satisfied by certain DP; DP can instantiate FR	Design parameters (DP)
Diagnosis of "bad" design concepts	Observable-fact abduction	Unacceptable or "bad" design concept	Certain design constrains and axioms lead to good design result	Violation of design constraints or axioms

Table 2
Examples of applying factual abduction in the Axiomatic Design.

Empirical fact	Applicable laws	Explanation
Triangle design matrix	Decoupled design has triangle design matrix	Violation of independence axiom
Full design matrix	Coupled design has full design matrix	Violation of independence axiom
System range lies outside the design range	Information content increases, as system range and design range apart	Violation of information axiom

research, we suggest carrying out two sequential abductive reasoning to gradually reduce the level of abstraction and increase the degree of confidence of the proposed design concept. The design intent/goal in the customer domain is firstly transformed to appropriate design target/objective in the functional domain, then the chosen design target is mapped to possible design concept/result in the physical domain.

2.3.3. Diagnosis of violating design constraints or design axioms

Even after design synthesis arrives at a set of possible design concepts, abductive reasoning can still be applied to diagnose the specific flaws of "bad" design concepts. Note that synthesis is always an iterative process at early design stages. Rather than directly abandoning those "bad" design concepts, it is often necessary to find the appropriate explanations and improve them accordingly. For instance, when certain design concept is asserted to be too "complex", the best thing to do is to firstly explain which type of complexity it has, then to take proper actions to simplify this design concept accordingly [16].

At early stages, "bad" design concepts are often resulted from violation of some design constraints or design axioms. In design, synthesis reasoning must always be carried out under a set of well-defined constraints. The violation of design constraints might cause unacceptable design concepts (e.g., too expensive for customers to afford, too complicated for mass production, etc.). In addition, design axioms are empirically generated from successful design experience and observation of good design practice. They can be seen as the result (or lessons learnt) of good inductive reasoning in the long-term. At early stages when everything is still relatively intangible, design constraints and design axioms are extremely valuable to guide designer's mental reasoning.

Factual abduction [9] can be applied here to explain the reasons why "bad" design concept emerge and prescribe the corresponding remedies to improve it. Specifically, observable-fact abduction produces factual reasons based on singular empirical fact and applicable laws. Table 2 summarizes several practical examples of applying factual abduction in the Axiomatic Design in terms of diagnosis of violating design axioms.

In design synthesis, when designers trace backward to seek for explanations of "bad" design concept, accuracy and efficiency are the primary considerations. To expedite this abductive diagnosis process, it is important to clearly define the typical features (i.e., empirical facts) of "bad" design and classify possible explanations into different types, so that designers can link observations and explanations more effectively via factual abduction. The complexity theory [16], which is complementary to Axiomatic Design, is a good example of such application.

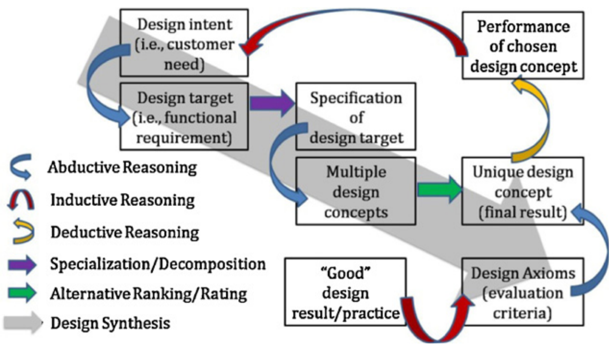

Fig. 1. The abduction-based synthesis reasoning process.

3. An abduction-based design synthesis process

Since a typical abductive reasoning involves both hypothesis generation and hypothesis evaluation, the proposed abduction based synthesis reasoning process must also consist of two phases: alternative creation and alternative selection. As shown in Fig. 1, the integrated synthesis reasoning process (i.e., the diagonal grey arrow in Fig. 1) involves three separate abductive inferences (i.e., the blue arrows in Fig. 1), which correspond to the three applications of abduction to design synthesis that we discussed in Section 2.3. Note that, although the proposed process has solid logic foundations, our purpose is not to make the design synthesis process completely logical, fully computational, and eventually automatic. But rather, we expect that this structured process can drive designers to subjectively think and reason in a more systemic and rational manner at early design stages.

3.1. The alternative creation phase of synthesis reasoning

(1) Elicit initial design intents.
Synthesis reasoning begins with eliciting design intents. There are many approaches (e.g., QFD [17]) that can structure "customer voices" on the market to identify the most promising opportunity as the initial design intent. The design intents determined at this step serve as the origin of synthesis reasoning.
(2) Organize design constraints as boundary conditions.
Boundary conditions of synthesis reasoning are various types of design constraints. They limit the consideration of possible hypothesis/explanation in the following reasoning steps.
(3) Propose appropriate design targets.
Consider design intents as the to-be-achieved consequence, an abductive reasoning is performed to propose specific design targets. This step links the entities between customer domain (CN) and functional domain (FR). Compared with the initial design intent, the design targets determined at this step can be viewed as the more explicit input of synthesis reasoning.
(4) Specialize proposed design target.
The relatively general design targets proposed in step (3) are further specialized into more detailed and concrete requirements. Specialization or decomposition (i.e., the purple arrow in Fig. 1) is a common operation that has been extensively studied by many existing design approaches.
(5) Ideate multiple possible design concepts.
Based on the specific design targets derived at step (4), designers employ another abductive reasoning to ideate possible design concepts into the physical domain (DP).

3.2. The alternative selection phase of synthesis reasoning

Given multiple design concepts from the above, some selection criteria must be introduced here, so that synthesis reasoning can arrive at a unique result through ranking or rating (the green arrow in Fig. 1). According to Peirce [1], in abduction, three aspects distinguish and determine a particularly promising hypothesis:

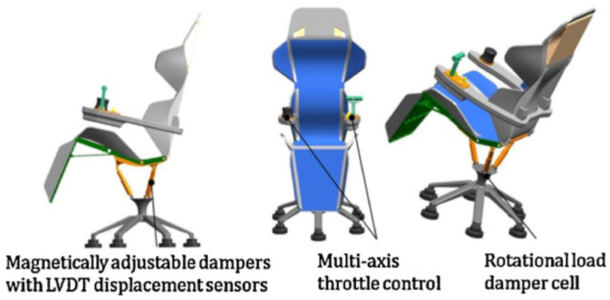

Fig. 2. The final design result of "UVA control device" example.

explanatory, testable, and economic. In design, that is to say that the design concept must properly satisfy/instantiate the design intent/target, it can be analyzed and evaluated, and it is satisficing. Peirce further suggests two specific criteria to evaluate the hypothesis: clarity and simplicity. In design, the criteria of "clarity" means that the ideated design concepts must be clear/concrete enough, such that its performance can be tested and evaluated; whereas the criteria of "simplicity" suggests that the simplest hypothesis is the best design concept. With no doubt, different design approaches will have different interpretations of the two criteria. For instance, in the Axiomatic Design, the simplest design is described as the functionally uncoupled design; whereas, in TRIZ [18], the simplest design is expressed as the design that consumes the least design resources.

For those "bad" design concepts according to the selection criteria, designers can choose to carry on the third round abductive reasoning to diagnose the specific flaws and propose respective improvements. The final output of synthesis reasoning can be further validated by ensuing deductive reasoning (i.e., the yellow arrow in Fig. 1) and inductive reasoning (i.e., the red arrow in Fig. 1) in design analysis and design evaluation.

4. An illustration example

The design assignment of this illustrative example is to develop a new Unmanned Aerial Vehicle (UVA) control device [19]. There are five designers, each with 3–5 year relevant product development experience in the aerospace industry, who participated in this example exercise. All participants followed the proposed synthesis reasoning process described in Section 3 to accomplish this team project. Below is the brief summary of the three abductive reasoning that were performed to arrive at the final design result which is illustrated in Fig. 2.

The first round abductive reasoning:

- Initial design intent (given): improve UVA pilot ergonomics.
- Applicable design knowledge (chosen): repeated stress injury is reduced if the pilot avoids static position and keeps moving body naturally.
- General design target (proposed): use natural body motion as control input.

The second round abductive reasoning:

- Specific design target (given): to translate natural body motions into 3–6 aircraft degrees of freedom.
- Applicable design knowledge (chosen): body motions can be captured by sensors.
- Specific design concept (proposed): a chair shape/structure UVA control device.

The third round abductive reasoning:

- Design problem (observed): the proposed design concept in last abduction is not user adaptive.
- Applicable design knowledge (chosen): user adaptive device should provide adjustable settings.
- Possible explanation (proposed): the supporting damper is not adjustable.
- Improvement (proposed): replace the traditional damper with a magnetically adjustable damper with displacement sensors.

5. Summary and conclusion

This paper discusses the applicability of abductive reasoning for design synthesis to support early stage engineering design. From a theoretical viewpoint, design synthesis can be modelled as an abductive reasoning activity from an abstract intent to a concrete concept. From an application perspective, different types of abduction patterns can be applied to address diverse challenges of design synthesis in practice. Based on these studies, we introduce an abduction based synthesis reasoning process to guide designers to go through two design phases (namely alternative creation and alternative selection) to reach the "good" synthesis result. For the alternative creation phase, given initial design intents in the customer domain, two sequential abductive reasoning are performed to firstly identify appropriate design targets in the functional domain, then to propose multiple possible design concepts in the physical domain. For the alternative selection phase, another abductive reasoning is carried out to diagnose those "bad" design concepts and prescribe corresponding improvement strategy.

We except that this research can deepen the understanding of design synthesis both theoretically and practically. By employing appropriate patterns of abductive reasoning at certain key points, the design synthesis process can become more systematic and effective. Specifically, the alternative creation becomes more structured and innovative, whereas the alternative selection becomes more accurate and efficient.

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