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Alternation of analysis and synthesis for concept generation

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ABSTRACT

Concept generation involves both analysis and synthesis activities interchangeably. In current practice, these two activities are often loosely defined and randomly performed. This paper presents a new method, called the Analysis Synthesis Alternation (ASA) approach, which treats concept generation as a proposition-making process and adapts the formal logic definitions of analytic and synthetic propositions to generate new concepts via two stages: ideation and validation. Both stages involve systemic alternations between analytic and synthetic propositions, but the alterations are performed in reverse reasoning directions. Experiment shows that ASA outperforms traditional brainstorming technique in both novelty and functionality.

1. Introduction

Concept generation is the most challenging activity in conceptual design, where functional requirements (FR) are transformed to design parameters (DP) under design constraints. Many analysis and synthesis activities take place during this transformation, which determines effectiveness of design processes and quality of generated concepts. In current practice, analysis and synthesis are often poorly understood, loosely defined, and carried out in an ad-hoc manner largely based on experiences, leading to design processes difficult to manage and design concepts hard to improve. For instance, with the Analytical Target Cascading [1] approach, the designer performs analyses repeatedly to "decompose" the problem via a top-down path, then leaps from the problem space to the solution space, finally followed by iterative syntheses to "combine" the solutions via a bottom-up path. However, the success of such a practice highly depends on effectiveness of those "heroic leaps" and the availability of known system architectures to navigate the decomposition of problems and the recombination of solutions. Also, such isolated treatment of analysis and synthesis activities hinders the designer from gaining various cognitive benefits of frequently alternating between different activities.

Both analysis and synthesis are important activities for concept generation in conceptual design. Most of current approaches treat design as a problem solving process, where the analysis operation plays a key role in analysing the given problem, task, goal, etc. Since conceptual design starts from a set of chosen functional requirements [2], many efforts have been devoted to the study of functional analysis. Nevertheless, it has been indicated by some previous studies that repeated problem analysis is by no means an effective means to support creative design [3]. On the other hand, synthesis is commonly recognized as an essential activity that determines the success of early stage design by different theories (e.g., Axiomatic Design [2], Function Behaviour Structure Model [4], General Design Theory [5], etc.). Many research efforts have been devoted to describe what constitutes a synthesis activity, and to prescribe different ways to carry out synthesis systemically. Yet, to date, the precise definitions of synthesis still vary significantly among different design research. The lack of a commonly agreed definition of synthesis greatly hinders the distinction of synthesis and analysis activities in practice.

Traditionally, the pattern of "alternation" is often confused with the pattern of "iteration" in design practice. In essence, the former is characterized by the successive occurrence of two different activities in turn with the purpose of achieving a progressive transformation, whereas the latter features the repeated repetitions of the same activity with the aim of gradually approaching the activity's ideal state (some easily solvable sub-problems for analysis activity or an integrated solution for synthesis activity). To date, the vast majority of existing studies failed to clearly distinguish the patterns of alternation from that of iteration. As a consequence, although there exists many studies of design iteration [6], few efforts have been devoted to investigate the pattern of alternation, except for some notable exceptions. For instance, Schon and Wiggins modelled design as a continuous alternation between "seeing" and "moving" [7]. On the other hand, the importance of alternating between analysis and synthesis has been implied by many past studies. The cycle of 'analysis–synthesis–evaluation' is widely accepted to be the dominating pattern at early design stages [3], and a number of methods have followed this cycle to structure their design process [8]. In the FBS model [4], Gero proposed a different cycle of "synthesis–analysis–evaluation". Additionally, Dorst and Cross observed that creative designs and expert designers are characterized by their constant alternation between problem and solution spaces [9].

This paper presents a new concept generation method, called the Analysis Synthesis Alternation (ASA) approach, which treats design

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as a proposition making process and uses the formal definitions of analytic and synthetic propositions from logic [10] to support concept generation via two stages. The ideation stage consists of an alternation between posteriori-analytic and posteriori-synthetic propositions; and the validation stage includes an alternation between priori-analytic and priori-synthetic propositions in a reverse direction.

2. A new Analysis–Synthesis Alternation approach

2.1. Classification of propositions during concept generation

At early design stages, the designer often uses spoken language to state, discuss, and justify his/her ideas to others in order to generate new concepts. Based on this observation, our Analysis Synthesis Alternation (ASA) approach treats concept generation as a series of "propositions-making" activities, where the designer systematically makes propositions to satisfy the targeted FR under constraints. In epistemology, a "proposition" is a particular type of sentence which declares a special kind of relational association between the "subject" and the "predicate" within the said sentence. The "subject" is what the sentence is oriented, and the "predicate" tells something about the subject. In the study of logics, two types of propositions are defined based on different subject–predicate relationships established by a sentence. An "analytical proposition" is a sentence whose predicate is "contained-within" the subject; whereas a "synthetic proposition" is a sentence whose predicate is "not-contained-within" the subject [10]. For example, "Bikes have wheels" is an analytic proposition because the predicate "wheels" is contained within the subject "bike". On the other hand, "Bikes are unsafe" is a synthetic proposition because the predicate "unsafe" is unnecessarily contained within the subject "bike".

In ASA, the analytic–synthetic distinction is used to characterize different kinds of relationships involved with the proposed design concepts. Because the predicate is contained within its subject, an analytic proposition in ASA yields a "specified-by" logic relationship, which suggests that the predicate is a "part-of" its subject. In contrast, since the predicate is not contained within its subject, a synthetic proposition in ASA creates a "realized-by" relationship, which indicates that the subject concept could be a possible "means-of" its predicate concept. For examples, the analytic proposition "Bike have wheels" defines a "part-of" relationship between "wheels" (i.e., the predicate) and "bikes" (i.e., the subject). Whereas, the synthetic proposition "Bike security is realized-by a U-lock" suggests that "U-lock" (i.e., the predicate) is a possible means to realize "bike security" (i.e., the subject), while there are also many other means available.

Furthermore, logic also recognizes the difference between priori and posteriori propositions. By definition, a priori proposition can be justified independent of subjective experience, whereas a posteriori proposition's justification must rely on subjective experience or external evidence. For example, "bikes have wheels" can be regarded as a priori proposition, because this statement is definitional and hence no need to query any evidence to determine if it is valid. On the other hand, "bikes are unsafe" is a posteriori proposition, because validation (or acceptance by others) of this proposition depends largely on an individual's experience whether he/she observed or was involved in a bike accident before. The priori–posteriori distinction of propositions is useful in organizing concept generation into two stages: ideation and validation. The former describes how individual pieces of a new concept are intuitively created, whereas the latter explains how the concept as a whole is systemically integrated and rigorously verified. The ideation stage relies more on the designer's heuristics and intuition to achieve the new concept's novelty, and the validation stage requires the designer's experience-independent apriority to secure the new concept's quality. As a result, the ideation and validation stage each involves making more posteriori propositions and priori propositions, respectively.

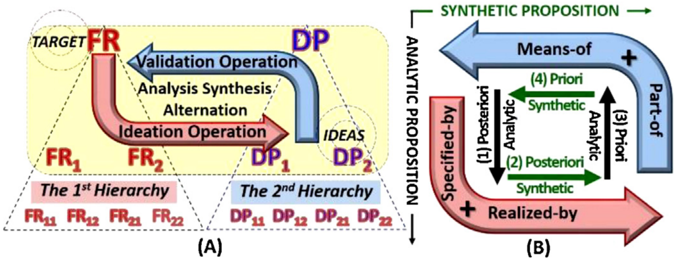

Fig. 1. Alternation of propositions during ideation and validation stages.

The combined consideration of both analytic–synthetic the priori–posteriori distinctions leads to a theoretically sound classification of design propositions: (1) posteriori-analytic, and (2) posteriori-synthetic during the ideation stage; (3) priori-analytic and (4) priori-synthetic during the validation stage. ASA prescribes a particular sequence among these four types of propositions to support concept generation. Although both distinctions of propositions are theoretically sound in logic, their application in practice is in no way straightforward. This is because people's interpretation of a real-world proposition is always influenced by their background, knowledge and experience. As a result, an analytic proposition to one designer might be regarded as a synthetic proposition by another. This is why ASA is best used in collaborative design [11], so that social constructionism (i.e., "two heads are better than one") is leveraged to distinguish different kinds of propositions and identify the truly valuable ones. That being said, the analytic–synthetic and priori–posteriori distinctions are both determined by team consensus.

Different propositions made by different designers must be properly organized. In engineering design, hierarchy is a commonly used structure to guide problem analysis, decision making, and optimization [12]. As explained above, analytical and synthetic propositions are of very different kinds and hence should be made mutually exclusive of each other. Furthermore, the subject–predicate relationships which they created are "logically orthogonal". Therefore, ASA proposes a two-hierarchy structure to organize various design propositions, as illustrated in Fig. 1(A). The 1st hierarchy is used to organize multiple "specified-by" (or "part-of") relationships derived from making analytic propositions. When different designers repeatedly make analytic propositions on a given subject (A), an ontological hierarchy can be established to include all its corresponding predicates (A_1 and A_2). Unlike analytic propositions, the "realized-by" (or "means-of") relationships created by making synthetic propositions cannot be organized hierarchically. This is because the predicates of synthetic propositions are "not" logically contained within their subjects. In order words, since these subject and predicate entities are not in the same "family", according to the strict definition of a hierarchy, they cannot be organized simply as the parent and children in a single hierarchy. Nonetheless, all the predicate entities resulted from synthetic propositions can be organized among themselves in a separate hierarchy (herein refer to as the 2nd hierarchy), with corresponding "means-of" relationships linked back to their corresponding subjects in the 1st hierarchy. In ASA, the 1st hierarchy, which represents functional requirements, is called the FR hierarchy; and the 2nd hierarchy, which represents design parameters, is called the DP hierarchy. This is analogous to the notion of "domains" in Axiomatic Design [2].

2.2. Alternation between analytic and synthetic propositions

ASA alternates between rigorously defined analytic and synthetic propositions in a particular sequence using the two hierarchy structure. As shown in Fig. 1(B), both ideation and validation stages include an alternation of analytic and synthetic propositions. The two stages differ from each other in terms of the distinction of priori–posteriori propositions explained in Section 2.1. In the ideation stage, the posteriori-analytic and posteriori-synthetic propositions are alternatively made to decompose FR