Abstract

One way to reduce potentially serious problems caused by modifications to the original design is to find out design thinking process of the original designer. The knowledge structure of design thinking process is represented, which is composed of design intent, design decision, design rationale and design operation. Semi-formal structure is adopted by the presentation, which means both the expressiveness and computability of the representation can be improved. Context in the design thinking process is defined, which can reduce complexity of the design thinking process. Independence between contexts that share an intent allows the designer to propose more assumptions about the design without necessarily affecting previous design thinking process. A graphical modeling system is established for capturing and formalizing the design thinking process.

1. Introduction

Usually, the results of design processes are like “snapshots” of the design process[1], however, they can’t describe the designer’s thinking process. Design thinking process involves the mental manipulation of information, as the designer forms ideas, engages in design problem solving, reasoning and decision-making. It can not only explain how the design process progresses but elaborate what motivations for design decisions or reasons for design procedures are.

Designers may write and draw on their notebooks to record important decisions and procedures concerning the design process. Some researches focused on the extraction of information or design rationale recorded in the design notebooks[2, 3], while the design thinking process won’t be captured completely in this way, for missing information which is not articulated by the designer. Therefore, more efforts should be made to substantiate and formalize the design thinking process with taking into consideration intents of the designers, rationales and methods of design decision-making and operation procedures of the design process.

2. Related works

There are four important elements involving in the representation of design thinking process: design intent, design decision, design rationale and design operation. These elements are not contradictory but complementary, therefore, more than one can, and indeed should, be included in a representation form of design thinking process.

The prime goal of design can be divided into artifact intent and process intent. Artifact intent means the goal on acquiring function, behavior and form of an artifact. Process intent is the aim for taking actions in the design process. Artifact intent is usually captured by feature[4], constraint[5] and function[6] of designed artifact, which can only reflect design intent indirectly. Several researchers[1, 7] take artifact intent as an independent element in their representations, and prove that explicitly represented intent has the advantages of allowing modular representation of arguments, forcing designers to articulate evaluation criteria and letting designers argue about them[8]. Compared to artifact intent, process intent is less concerned with, although process intent is important for changing and reusing the process sequence. A few related researches only limit their representation of process intent for operating computer tools[9, 10].

Making decisions and executing operations appear alternately as the design thinking process evolves and
they are indispensable activities[11] involved in design thinking process. However, not many representations concentrate on both of them due to different application situation, which sacrifices the completeness of representation.

Design rationale is the knowledge for reasons behind design procedures or decisions/artifacts. Argumentation-based design rationale researches are developed for representing decision rationale. Most of them are originated from IBIS[12], such as gIBIS[13], DRed[14]. Procedure rationale is mentioned only in[10], which is captured and explained automatically.

More efforts are made on representing intents and rationales for artifacts/decisions than for the design process/procedures. Design activities are realization of design decisions and the result of them also affects the next decision of designers. Therefore, design operations, process intents and procedure rationales are all needed to be described in the representation of the design thinking process for complete expressiveness.

In this paper, we present a more complete knowledge representation of design thinking process which involves all the elements mentioned above. Based on the semiformal structure learned from argument-based rationale, we can provide several computable services.

3. Knowledge structure of design thinking process

Design thinking process is the mental process that the designer generates design concept, makes design decision and solves design problem using expertise, knowledge and contextual information to satisfy design intents. The design thinking process model is composed of design intent, design decision, design rationale and design operation.

Design intent describes the objectives, plans, ends and desires that stimulate and instruct the designer’s thinking process. Design intent is composed of several sub-intents, which can also be decomposed continually. When the design intent is divided into some level of abstraction, the designer can propose options or take operations to achieve it directly and this type of intent is called elementary intent. Elementary intent is defined as the minimal unit of design intents, which can not be broken up further. The more specific the intents, the more specific the artifacts or operations would be.

Figure 1 is an example for explaining these concepts in detail. Suppose the designer wants to design a bill deposit mechanism for an ATM. The primitive design intent is “to design a bill deposit mechanism for an ATM”, which is labeled as I1. In order to achieve this intent, the designer may decompose the intent into several sub-intents, e.g. “to separate piles of bills” (sI11), “to transport bills” (sI12), “to identify denomination of bills” (sI13) and “to store bills” (sI14). The relationship of these intents is decomposed-into(AND), which means only when all of them are achieved, I1 can be achieved. Then the designer chooses to realize sI11 first, and sI11 is replaced by an elementary-intent “to design isolation mechanism first” (eI111). Replaced-by(OR) relationship means that a general intent is refined into a more specific one.

![Design intent tree](image-url)

**Figure 1. Design intent tree**

Design decision is the ultimate solution that the designer makes after analyzing and comparing several design alternatives against criteria. These alternatives are called design options which are generated during the process for the designer to realize the design intent. For example, in order to realize the eI111 in Figure 1, the designer may propose several options such as vacuum-type(O1), friction-type(O2) and swing-out-type(O3) isolation mechanism. It is important to allow designers to propose as many plausible options as possible in the design process, for they can come back
to other options when a selected option is proven infeasible. In this example, the designer chooses the vacuum-type as the decision (D1) temporarily.

Operation is the action whose execution should result in the realization of the design intent, e.g., using a CAD system software to generate solid models of the products, searching for similar solutions or communicating with other designers. Sometimes a series of operations are needed to realize the design intent. The meaningful collection of operations the designer performs to achieve design intents is defined as an operation set. For example, an operation set about “optimizing parameters” may be composed of several operations such as “starting up CAE software”, “inputting parameters”, “deploying conditions”, “selecting algorithm” and “computing”. In our example shown in Figure 1, Op1 (drawing the draft of D1) is taken by the designer, which promotes the next intent I2 (to design the vacuum-type bill isolation mechanism).

Design intents explain “what” the designer does in the design process, while design rationales illustrate “why” the designer does so or “why” the design proceeds in this way. The expertise, experience and contextual information that the designer considers to elaborate reasons for decisions and operations are design rationales. In our study, two kinds of design rationales are considered: evidences for proposing design options and criteria for evaluating different options and making final decisions.

Evidences are accepted principles or instructions that the designer follows to generate design options achieving design intents. Design evidence has different categories and levels of abstraction. It may be a physical principle, condition or constraint in the design requirement, and even a formula in the design handbook. Specially, design evidences can be several assumptions that the designer takes according to his/her own expertise and experience. Evidences for options in Figure 1 are principle of vacuum (E1), principle of friction (E2) and principle of centrifugal force (E3) separately.

Criteria are standards against which the designer can compare or judge design options and making decisions. Just like design evidences, design criteria also have different categories and levels of abstraction. Criteria that the designer refers to in the example may be cost (C1), size (C2) and if the bill easily to be mangled (C3). The designer compares options according to these criteria and chooses the most proper one.

4. Context in design thinking process

4.1 Definition of context

Design thinking process is the long chain of the designer’s thought. It is composed of a series of design episodes. Design episode represents a collection of elements sharing a primitive intent. An episode starts when a primary intent is generated and ends when decisions have been made or operations have been taken that satisfies the intent. For example, all the elements (intents, options, decisions, rationales and operations) in Figure 2 constitute an episode around I1.

There are two kinds of logical relationship among these elements: and and or. If the relationship among elements is and, all of them must exist simultaneously to satisfy the primitive intent of the episode. Otherwise, if the relationship is or, only one of them needs to be considered. The dependency relationship of the episode decides that there will be several assemblies of elements that can achieve the intent.

Design context is one of the assemblies of elements in the episode which can satisfy the primitive intent. For example, a context of the episode in Figure 2 is outlined with dashed and curved shape in Figure 3(a). Based on the dependency relationship of elements in the episode, there may be other contexts about the same primitive intent. Figure 3(b) represents another context of the episode when O2 is taken as the decision.

Design context can represent different assumptions about the design episode, such as selecting different options, referring to different criteria or evidences, even choosing different intents to achieve. Therefore, representation of design context allows the designer to explore different routes of the design thinking process asynchronously. The only thing that the designer needs to do is to setup a new context with changed elements in the design episode.
The change of elements in a context won’t have effects on elements in other context, even if they share a primitive intent. All the values of elements of a context are defined as local values, and won’t cause a conflict, even when the same variable gets different values in different contexts. Thus, plausible modifications to part of an episode can be made by creating a new context to observe the influence without necessarily losing any previous design thinking process. Elements in a context can be reasoned based on the dependency relationship in the context.

4.2 Representation of context

The design context influences the design thinking process by providing contextual information that is considered by the designer when proposing options, making decisions or taking operations. The contextual information is classified into three categories: variable, condition and constraint.

Variable is the expression of possible product or some aspects of product such as function or behavior in the design episode. For example, variables of the episode around “to decide the tooth number of gears” can be “zp” and “zw”, which represents tooth number of pinion and wheel separately. Condition describes values of variables in the episode which have been known when the intent is produced. Constraint is the confinement or restriction on variables in the design episode. For example, it can be equations and inequalities that restrict values of variables.

Contextual information can be inherited by design rationales in the context. On the other hand, the results of decisions or operations are added to the contextual information as conditions or constraints.

4.3 Consistency maintenance in context

Eight types of basic relationships among elements in a design context are defined as following:

- Replaced-by <Intent, Intent> means that if an Intent I1 is related to Intent I2 through a replaced-by relationship, then satisfying I2 facilitates satisfying I1.
- Decomposed-into<Intent, Intents> is the relationship between an intent (say I1) and two or more intents (say I2 and I3), and only when both I2 and I3 are achieved I1 can be achieved.
- Achieve<Option, Intent> means that the option is the alternative solutions proposed by the designer to achieve the design intent.
- Decided-by<Option, Decision> means that the option is selected by the designer to be the final decision.
- Realized-by<Decision, Operation> is the relationship between decision and operation, meaning that the designer turns the decision in mind into actual activities.
- Follows<Option, Evidence> is the relationship that the option is proposed by conforming to the evidence. The plausibility of this relationship is the measure of how strongly that the evidence can support the option with respect to the intent that the option is related to. The plausibility is decided by the type of the evidence that the option follows. If the type is assumption, then the plausibility is low, and if the type is fact, then the plausibility is high.
- Refers-to <Decision, Criterion> is the relationship that relates a decision to the criterion that it refers to for selecting options. Normally, there are multiple criteria for a decision to refer to, so this relationship is represented as a decision matrix.
- Promotes<Operation, Intent> is the relationship that relates an operation to an intent, meaning that the result of the operation will initiate a new intent.

Our representation is not expressive and strict enough to do design reasoning through the whole design thinking process. However, design context helps divide the long chain of design thought into
individual and manageable chunks, which decrease the complexity of the design thinking process. In addition, taking the advantage of the links (logical relationship) among elements, we can check and maintain the inconsistency occurred in the design thinking process. For example, if there are no adaptable decisions or operations to achieve the intent, or new obtained information is conflict with the original contextual information (i.e. condition and constraints), inconsistency occurs. Any changes of an element in the context can be propagated to other elements related to it. The detailed algorithms and computable services will be introduced in another paper.

5. Prototype system

A prototype system MindDigger based on the knowledge representation is developed to allow designer to model design thinking process when performing a variety of design tasks.

Given the knowledge representation of the design thinking process, it would be a difficult task for designers to learn it and record their design thinking process with our representation manually. Hence we propose a graphical modeling interface to help the designer for inputting design thinking process.

The graphical user interface which is shown in Figure 4 is user friendly. On the left of the interface is the hierarchy of the design thinking process. When the designer selects one of the episodes, the tree structure of the selected episode will be unfolded. As the same time, the elements and their relationships of this episode will be represented as nodes and links in the graphical modeling region which is on the right of the interface. The tool provides several graphical symbols for representing the elements and relationships. The user can express his/her design thinking process simply by dragging some symbols from the toolbox and relating them without knowing what the system will do in background. Figure 4 shows the graphical model of the example in Figure 1.

This system can also help the designer in every step of design thinking process record, so that the input design thinking processes are grammatically correct. It should point out syntactic or semantic errors, if any. The graphical user interface can also help the designer in expanding and modifying the grammar rules to suit the designer’s domain. This guidance will be very helpful to a novice designer until he/she becomes familiar with the syntax.

The designer can create, modify, delete, and manage contexts of the design thinking process with context manager provided by the system. Figure 5 is the example in Figure 3 (b).

6. Conclusion and future work

The knowledge structure of design thinking process is represented, which is composed of design intent, design decision, design rationale and design operation. Both expressiveness and computability of the language have been improved with the use of semi-formal representation structure. Context in the design thinking process is defined, which can reduce complexity of the design thinking process. Independence between contexts that share an intent allows the designer to propose more assumptions about the design without necessarily affect previous design thinking process.

A graphical design thinking process modeling system MindDigger is developed for modeling the design thinking process and managing the design context. Future work involves the development of an approach to recording the design thinking process without disturbing the designers, automatic extraction of templates of the design thinking process, the extension of the prototype system for supporting collaborative design.

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8. References


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**Figure 4. Graphical modeling interface**

**Figure 5. Context manager**