Study of mental iteration in different design situations

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Mental iteration in engineering design is a repetition of cognitive activities occurring in designers' thinking process. While the importance of mental iteration has been recognized, the current understanding about it is still very limited. In this paper, we propose a framework to study mental iteration in different design situations. A cognitive activity model of conceptual design is developed to identify and capture various loops of cognitive activities. An experiment is conducted to study the effect of design problems and constraints on the behavior of mental iteration. The results indicate differences of iterative behaviors in response to different problem types and constraint conditions.

Keywords: mental iteration, cognitive model, protocol analysis, conceptual design, design process

Engineering design is the process of creating and evaluating specifications of artifacts whose form and function achieve stated objectives and satisfy specified constraints (Dym, 1994). It is commonly accepted that this process is iterative. Requirements and constraints become more concrete after iterations of problem clarification and definition. Design concepts are created and elaborated after iterations of idea generation and evaluation. Iteration is an integral part of the design process.

Design iteration can be recognized in different forms, ranging from simple task repetition to heuristic reasoning processes (Costa and Sobek, 2003). Based on what is repeating, one can classify iteration into two primary types: iteration of design tasks and iteration of cognitive activities. For the first type, iteration is recognized as repeating design tasks in a design project, which is often carried out by a team of designers. For the second type, iteration is recognized as repeating cognitive activities in a single designer's mind when he/she is performing design tasks.

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Iteration of design tasks is relatively explicit because repetition of already completed or ongoing tasks in design projects can be clearly seen. This type of iteration can be unfavorable, although sometimes necessary, to designers because it usually leads to longer design time and higher design cost. Much research (Tjandra, 1995; Eppinger et al., 1997; Krishnan et al., 1997; Smith and Eppinger, 1997; Smith and Tjandra, 1998; Sobek et al., 1999; Costa and Sobek, 2003) has been carried out to observe and understand task level iteration and to devise methods and tools for managing iteration of design tasks and improving product development processes.

On the other hand, mental iteration is less explicit because it occurs inside designers' mind. However, one can observe that designers' thinking processes are iterative through design sketches and protocol analysis. It has been suggested that iterative design behavior is a natural feature of design competency (Bucciarelli, 1996). During design, designers iteratively explore problems for better understanding, generate and evaluate ideas for better ones, and operationalize concepts for better solutions.

Although the important roles of mental iteration in engineering design have been widely recognized, there has been little research that specifically studies mental iteration and provides insights on how to manage it. The behavior, mechanism, and influence of mental iteration have not been clearly understood. This lack of understanding limits our ability to provide effective methods and tools for improving current practice of conceptual design.

In this paper, we focus on mental iteration in conceptual design. As the first step of our mental iteration research, the following questions are addressed:

- *What is mental iteration? How does it occur?*
- *Are there different types of mental iteration?*
- *How does the mental iteration behavior relate to different design situations?*

To answer these questions, we take a cognitive modeling approach. Based on critical literature survey and our previous work (Benami, 2002; Benami and Jin, 2002), a cognitive activity model of conceptual design is developed to capture key cognitive activities and their relations. Data from protocol studies are used to verify and adjust the model. From the model, different types of iteration loops are identified and an experiment is conducted to investigate design mental iteration in response to different design situations. In this research, *design situation* is defined by two attributes namely, *problem type*—i.e., creative design versus routine design—and *constraint condition*—i.e., non-constrained versus constrained problems. Since the focus of this research is mental iteration, in the following, we will use 'iteration' and 'mental iteration' interchangeably.

1 Mental iteration in design

Most cognitive models and design models that describe cognitive processes in design (Finke et al., 1992; Maher et al., 1996; McKoy et al., 2001; Benami and Jin, 2002) indicate the iterative nature of design cognition. Schön (1983) and Schön and Wiggins (1992) viewed design as a sequence of seeing–moving–seeing cycles. Dorst and Cross (2001) applied observation from their protocol studies to the co-evolution model (Maher et al., 1996) and found that creative design seems more to be a matter of developing and refining both the formulation of a problem and ideas for a solution, with constant iteration of analysis, synthesis and evaluation processes between problem-space and solution-space.

To date, there has been little research specifically addressing issues of mental iteration in engineering design. Adams and Atman (1999, 2000), Adams (2001), Adams et al. (2003) studied iterative behavior in engineering student design processes and revealed both behavioral and performance differences between freshman and senior students in their engineering design coursework. Iteration was defined as a goal-directed problem solving process and modeled as a sequence of transition behaviors between information processing and decision-making. Their results suggest that iteration is a significant component of design activity that occurs frequently. In addition, measures of iterative activities correlate positively with design success and senior students iterate more effectively than freshman students. The focus of this pioneer work was on identifying designers' iterative transition behaviors, such as monitor, search, verify, plan, redefine and capture, and relate them to design competency. The understanding of the roles and patterns of these behaviors helps develop more effective instructional approaches for teaching design and provides helpful references for the development of further research on mental iteration.

The research on mental iteration in this paper differs in focus and approach from the work of Adams and Atman (1999, 2000). Our long-term research goal is to devise better tools to support idea generation in conceptual design. To do so, we first need to understand *how* designers think iteratively and what *information* is generated and manipulated during the thinking process. We believe this understanding will serve as a basis for us to design computer tools that help designers to represent, record, and process design information and facilitate idea generation. Therefore, in our study of mental iteration, we take an idea generation approach and focus more on the 'contents' or 'ideas' that are 'flowing' during the iteration process. We are concerned with what ideas or contents are generated, what roles they play in designers' cognitive activities, and how they are enhanced, composed, adopted, reused, discarded, or lost. We aim to understand how mental iteration can help or hinder idea generation, composition, and evaluation. As the first step of this endeavor, we developed a cognitive activity model of conceptual design and introduced iteration loops for modeling mental iteration. Our experimental study results indicate the differences of mental iteration in different design situations defined by problem types and constraint conditions. In the following, we first present the cognitive activity model of conceptual design and introduce the mental iteration loops based on this model. After that, the experimental study and the results will be discussed.

2 *A cognitive activity model of conceptual design*

Both design researchers and cognitive scientists have developed various process models to study human creative behavior in design. The models developed are often based on observations of design processes and analysis of design protocols. French (1985) developed a model of design process that includes activities of analysis of the problem, conceptual design, embodiment of schemes, and detailing. Ullman et al. (1998) developed a model of the design process based on empirical data. Maher et al. (1996) introduced a co-evolution model that describes creative design process as 'co-evolution' between problem-space and design space. Cross (2000) described a four-stage model of the design process, which is composed of exploration, generation, evaluation, and communication. He also developed a general model of creative strategies (Cross, 2000) to describe how exceptional designers solve the creative design tasks. Kruger and Cross (2001) developed an expertise model of the product design process to study cognitive strategies in design. Shah et al. (2001) proposed a model of Design Thought Process to describe generation and interpretation of ideas. Benami (2002) introduced a cognitive model of creative conceptual design to capture interactions between cognitive processes, design entities, and design operations.

In the field of cognitive science, Finke et al. (1992) proposed the Geneplore model, a general model of creative cognition that can be applied to the conceptual design of products. The majority of the cognitive processes in the Geneplore model have been empirically identified in an engineering design experiment (Shah, 1998). Jansson and Smith (1991) proposed a theoretical model of the conceptual design process, which describes the movement between configuration space and concept space.

Most design process models explicitly represent design activities and their successive relations. In these models, the focus is on clarifying work or thinking steps involved in design rather than capturing what information is generated by these steps and how the information is processed through various iterations. The cognitive models mentioned above, on the other hand, treat the design process as a single iteration loop that provides little distinction of different types of iteration including their roles and mechanisms in conceptual design. To study mental iteration in conceptual design, we need a model that can identify cognitive design activities and address information generated from, and used by, these activities. The model should also be able to capture various types of iteration loops as part of the design process.

2.1 Cognitive activities and their relations

Following Benami and Jin (2002), we propose a cognitive activity model of conceptual design based on four key cognitive activities, namely, *analyze problem*, *generate*, *compose*, and *evaluate*, as shown in Figure 1. In our previous work (Benami and Jin, 2002), the generative processes include memory retrieval, association, and transformation. We map memory retrieval to *generate* activity and group association and transformation processes together as *compose* activity in our model. For exploratory processes, which are problem analysis and solution analysis, we interpreted them as *analyze problem* activity and *evaluate* activity, respectively.

The model shown in Figure 1 recognizes different phases of the idea generation process. This process view and our focus on 'contents' led us to describe our model using IDEF0 (Mayer, 1992), a language designed for modeling functional activities. IDEF0 represents activities of a given process in terms of its functional identity (i.e., name) and four distinctive interfaces, namely, input, output, control, and mechanism. In IDEF0, the contents generated by one activity as output can serve as input, control, or mechanism, of another activity. This explicit representation of content-based relations between activities makes it possible for us to identify mental iteration loops by following the 'flows' of design contents between the cognitive design activities. As an analysis tool,

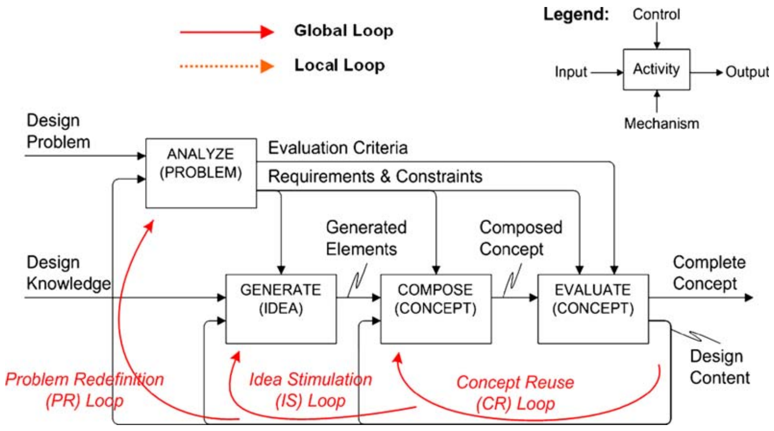

Figure 1 A cognitive activity model of conceptual design

IDEF0 assists modelers in identifying what functions are performed and what is needed to perform these functions (Mayer, 1992).

Although the model in Figure 1 is a cognitive model of the conceptual design process, not design iteration per se, the IDEF0 representation of flows of contents between the activities clearly shows what kinds of iterations are possible, where the iterations occur in the design process and how the iterations may interact with the cognitive activities and contribute to the overall design process. In the following we briefly describe each key cognitive activity. The detail of their sub-activities can be found in Chusilp and Jin (2004).

- *Analyze problem* involves understanding of the problem on hand and exploring requirements and constraints that need to be satisfied and maintained by the design. Through problem analysis, design goals are set, and constraints and requirements are defined. During design, the problem definition may be elaborated or revised, and the definition change will result in changes in constraints and requirements. As part of problem analysis, solution criteria are also determined from design goals, as indicated in Cross's (2002) General Model of Creative Strategies.
- *Generate* involves generating new ideas. Given problem requirements and constraints, designers retrieve from their memories relevant information and knowledge to create initial design ideas. Based on Finke et al. (1992), Oxman (2002) and our previous work on cognitive modeling of creative design (Benami and Jin, 2002), we include in *generate* activity not only memory retrieval but also perceptual stimulation that can act in response to iteration and stimulate designer's ideation.

- *Compose* involves the evolution of initial design ideas into identifiable design concepts (Gero and McNeill, 1998; Suwa et al., 1998; Benami and Jin, 2002). This activity is performed when designers combine new ideas generated from their mind with the ideas and/or concepts generated from previous iteration cycles. The combined ideas are then further transformed into more matured design concepts. Although many models treated *compose* as part of *generate* (Finke et al., 1992; Benami and Jin, 2002) differentiating the two provides opportunities for us to study how iteration interacts with idea generation and evolution.
- *Evaluate* is carried out to assess composed concepts against design requirements, constraints and criteria. As an exploratory cognitive process (Finke et al., 1992), *evaluate* is performed by designers to ensure a generated design concept is relevant, useful, and good. Relevance and usefulness of a concept are determined against design requirements and constraints, while goodness depends on design criteria.

2.2 Iteration loops

An iteration loop can be identified from circulating along cognitive activities. Types of iteration loops can be classified by the activities and information flows involved in the loop. As shown in Figure 1, our cognitive activity model of conceptual design identifies three iteration loops embedded among the four major activities. They are *problem redefinition loop*, *idea stimulation loop*, and *concept reuse loop*.

- *Problem redefinition* loop (PR loop) is the looping through activities of *analyze problem*, *generate*, *compose*, and *evaluate*. In this loop, after a concept is examined against the problem requirements and constraints by a designer, the result may lead the designer to re-think the current definition of the problem. When the need for redefining the problem is realized, the designer may either elaborate the original definition to introduce subproblem definitions or he or she may revise the original definition. Either way, this change will lead to the change of problem requirements and constraints. Problem redefinition loop allows expanding problem-space as well as the co-evolution of problem-space and solution-space (Maher et al., 1996). This loop can provide more information to facilitate creativity.
- *Idea stimulation* loop (IS loop) involves activities of *generate*, *compose*, and *evaluate* activity. In this loop, both previously used and un-adopted concepts may stimulate the designers' idea generation process. Our previous research has shown that there exist patterns of stimulation in which certain type of intermediate design concepts,

e.g., behavior rather than form and function, appears to be more effective in stimulating idea generation (Benami, 2002; Benami and Jin, 2002). It can be expected that more iterations along the *idea stimulation loop* may increase the number of newly created ideas.

- *Concept reuse* loop (CR loop) runs through *compose* and *evaluate* activities. In this loop, designers use existing ideas and concepts to compose new ones. It can often be seen that designers pick up previously generated ideas or concepts and reuse them in the new design context either in its original form or with modifications. It can be expected that the *concept reuse looping* can increase opportunities of having better use of created ideas.

We call these three iteration loops among the four key cognitive activities *global iteration*. Apart from global iterations, there are *local iterations* within each key cognitive activity (analysis loop, generate loop, compose loop, evaluate loop). *Local iteration* is the consecutive repetition of a cognitive activity and is carried out by designers to explore and evolve ideas until the 'desired state' of the ideas is reached so that the design can be moved to the next activity.

2.3 Comparison to other models

The cognitive model of conceptual design described above was conceived from our previous research (Benami and Jin, 2002) and influenced by other researchers' work (French, 1985; Dzbor, 1999; Cross, 2000; Dorst and Cross, 2001; Kruger and Cross, 2001). It shares some features of other models, e.g., iteration of problem and solution, which is described as co-evolution between problem-space and solution-space (Dorst and Cross, 2001), iteration of problem definition (Dzbor, 1999), feedback from the evaluation stage back to the generation stage (French, 1985; Cross, 2000). However, our model describes the conceptual design process in terms of *cognitive activities* and mental *iteration loops*. This integrated representation opened possibilities for us to explore how design mental iterations can have an impact on the design process and design performance. Another distinction is that the model description is based on IDEF0. The differentiation of the four interfaces in IDEF0 (i.e., *input*, *output*, *control*, and *mechanism*) allows us to explore relations between the cognitive activities and identify roles of various contents in mental iteration.

In addition, it is interesting to see that though we take a different approach from Adams (2001) to identify and classify iteration loops, there are some similarities in the results. In her work, types of design 'cycles' were obtained from critical literature review and defined by activities involved in the transitions of information processing and decision-making. Their iterative design cycles include problem scoping, solution revision, coupled problem scoping and solution revision, and self-monitored cycles. While these cycles are similar to our iteration loops, differences do exist. Our model includes idea stimulation loop and concept reuse loop that capture the idea generation phenomenon in conceptual design. On the other hand, the self-monitored cycle does not explicitly appear in our model but is implicitly embedded in all types of iteration loops as a part of *control* of the cognitive activities. These differences provide opportunities for us to understand the idea generation aspect of mental iteration, e.g., how iteration and cognitive stimulation are related and what roles design contents play in idea generation through iterations.

3 Experiment

Engineering involves various types of design problems of which each has specific requirements and constraint conditions. For example, engineers in a space exploration organization often work on new designs that they have never experienced before. On the other hand, engineers in a washing machine company may frequently work on the designs that are similar to the previous ones. Moreover, the requirement of minimizing weight for ship design may not be as critical as that for airplane design. In order to provide effective support for conceptual design, we need to know how different design situations may involve or require different mental iterations.

For the experiment presented in this paper, we characterize design situations with two factors, i.e., problem types and constraint conditions. Design problem type can be either *creative design* or *routine design*, and constraint conditions may be either *constrained* (or more constrained) or *non-constrained* (or less-constrained). In the future, we plan to consider other factors, including domains of the design, experience of designers, and types of constraints (time, parametric, non-parametric).

3.1 Objectives

We conducted protocol studies using the *think-aloud* method (Ericsson and Simon, 1993; Gero and McNeill, 1998) with two objectives in mind. First, protocol data are used for evaluating and revising the proposed model. The model presented in this paper is the result of many revisions. The second objective is to investigate the process of mental iteration with regard to the types of design problem, i.e., creative design versus routine design, and constraint conditions, i.e., non-constrained problems and constrained problems.

3.2 Hypotheses

For the second objective stated above, we developed and tested the following hypotheses.

- *Creative design involves more iterations than routine design*. It can be expected that in creative design, designers are not familiar with the problem so they need to think more iteratively to understand the problem and generate solution ideas.
- *Imposing constraints leads to more iteration*. For more constrained design problems, designers often need to adjust their solution ideas to satisfy multiple constraints. So it is conceivable that they need to carry out more iteration to complete their tasks.

3.3 Experimental design

The design and analysis of the experiment were based on Design of Experiments (Montgomery, 2001; Myers and Montgomery, 2002). Our experiment employed 2^2 factorial design. Sixteen participating subjects were equally divided into two groups, Group 1 and Group 2. Each subject worked on two design problems, a creative one and a routine one. Additional constraints were imposed on the problems given to the second group, i.e., Group 2. Totally there were four treatment combinations, as shown in Table 1, with eight replicates in each treatment combination. Analysis of variance (ANOVA) was performed to assess the statistically significant effects of problem types and constraint conditions and their interactions on the number of iterations, frequency of iterations, and percentage of each type of iteration loops. Since there was more than one dependent variable, multivariate analysis of variance (MANOVA) was carried out to reassure the appropriateness of ANOVAs. The effects were qualitative so the analysis was done in *coded* unit where -1 represents low setting and $+1$ represents high setting. For problem type, creative design is defined as the low setting and routine design as the high setting. For constraint condition, non-constrained condition is defined as the low setting and constrained condition as the high setting.

3.4 Subjects

Subjects in our experiment included 1 senior and 15 graduate students of the 2003–2004 academic year at University of Southern California. Two of the graduate students were industrial and systems engineering majors and the rest were in mechanical engineering. Thirteen of them were male and the other three were female. Participation was on a voluntary basis.

Table 1 Subject groups and treatment combinations

Subject group	Treatment combination	Problem type	Constraint condition
Group 1	Non-constrained creative design	−1	−1
Group 1	Non-constrained routine design	+1	−1
Group 2	Constrained creative design	−1	+1
Group 2	Constrained routine design	+1	+1

3.5 *Procedure*

Although the think-aloud method can reveal the sequences of subjects' thinking process, it is important to note that subjects are often neither familiar nor comfortable with speaking out loud while thinking. Therefore, it is necessary to train the subjects to become more familiar with the method. In our experiment, all subjects were tested individually in a quiet room to prevent distraction. Before starting the experiment, a brief instruction with a warm-up task was given to the subjects so that they can get used to thinking aloud. Each subject was assigned to first solve the creative problem and then the routine problem. Because subjects might get tired after solving the first problem, a 15-min break was taken after they finished the first problem. There was no time limitation but on average, subjects spent approximately 15 min for understanding the experiment procedure, 30 min for a warm-up task, 50 min for solving design problems with a break. The whole experiment sessions were video taped by two cameras: one from the top to capture their sketches and the other from the front to capture their gestures.

3.6 *Design problems*

Although there is no common classification of design problems, researchers have shown that design problems can be classified in accordance with an assessment of knowledge or how complete is the available knowledge in solving design problems. In Brown and Chandrasekaran (1985), Coyne et al. (1987), Gero (1991), and Schmitt and Chen (1991), design problems are classified into creative, innovative, and routine designs. In Dym (1994), three classes of design problems are identified, i.e., creative, variant, and routine designs. More *non-orthogonal* dimensions of design problems were also suggested by Frost (1994). The terms *creative* and *routine* in this study are used as a relative measure. Creative design refers to the design that has more in its own originality and appears less elsewhere, while routine design refers to the design that is more understood by the designer. The creative design problems used in our experiment are equivalent to the design between Dym's Class 1 and Class 2 designs (1994), and between Gero's creative and innovative design (1991). The routine design problem used in this experiment is more or less equivalent to Dym's Class 3 design (1994) and Gero's routine design (1991).

In our experiment, the chosen design problems must be suitable to the subjects, who are senior and graduate students. Based on the above considerations, we created the following design problems and constraints.

3.6.1 Creative design problem: self-powered personal transporter on snow

The creative design problem selected for this experiment is:

'Today ski and snowboards are widely used as personal transportation tools on snow. But, to be able to use them, a lot of skill and experience is required that normally a user cannot learn within one day. Moreover, ski and snowboards cannot run uphill because they are moved by gravity. Your task is to design other options of personal tools for transportation on snow. The design must be human-powered (powered by the user himself or herself) so that it can run without help from an engine or gravity. The design must allow the user to control direction and the brake. In addition, it should not require much time to learn how to use it.'

This problem is selected because it is new to the subjects and it does not require much technical knowledge to solve. In addition, the problem is relatively open to various kinds of solutions. For subjects in Group 2, i.e., the group with constrained problems, the following constraints are additionally imposed:

'Your design must satisfy the following constraints:

- *Weight less than 30 kg (user can carry it by himself alone).*
- *Fit into full size sedan car trunk (~ 1.5 m × 0.7 m × 1.0 m).*
- *The cost to build should be less than \$100.'*

3.6.2 Routine design problem: power transmission system

The routine design problem selected for this experiment is:

'Your task is to design a concept of a power transmission system that can transmit rotation between two shafts on the same horizon plane and reduce the speed from 2000 rpm to 100 rpm. The positions of input and output axes are shown in Figure 2. You do not need to concern about the strength of system components.'

For subjects in Group 2, the following constraints are additionally imposed:

'Your design must satisfy the following constraints:

- *Fit into the box space (2.0 m × 1.6 m). No vertical space limit.*
- *Use only gears (no belt, no chain).*
- *The diameter of each gear must be bigger than 0.1 m and smaller than 0.5 m.'*

The focus of this experiment was to observe how subjects think iteratively in the conceptual design phase in different design situations. The design problems we chose, on the one hand, are real design problems that require the subjects to develop specific solutions. On the other hand, the sizes of the problems are not too large for us to capture and analyze the protocols. For our experiment, all subjects had limited work experience and little experience of skiing, whereas they knew and had seen gears and transmission systems. The experimenter talked to each subject before the experiment to confirm that he/she perceived the selected creative problem as creative design and the selected routine problem as routine design. The content of the problem was not mentioned in the interview because subjects' perception might change if they knew the problem before hand.

3.7 Encoding

The analysis of protocol followed the following steps. First, the verbal protocol recorded from the design sessions was transcribed. The next step was activity matching. The transcript of a given subject was divided into segments, with each segment corresponding to one cognitive activity performed by the subject. In the third step, the four interfaces of each cognitive activity were identified and encoded using our coding

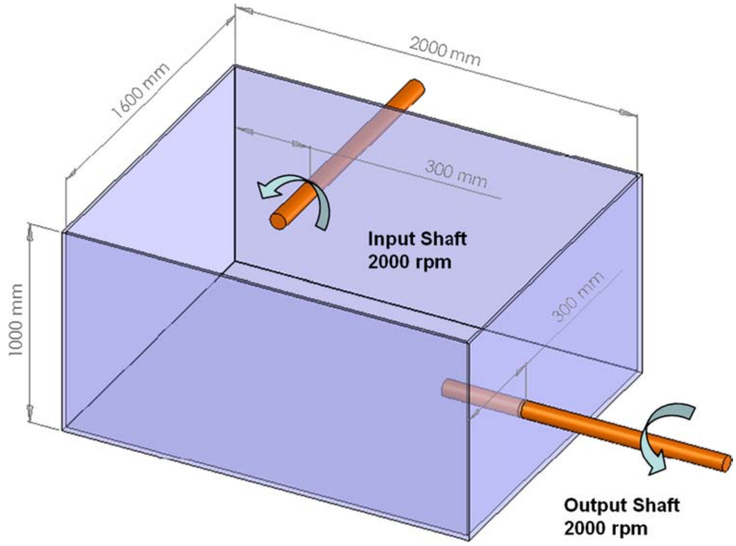

Figure 2 Power transmission design problem

scheme described in Appendix A. The coding scheme is designed to represent four key cognitive activities and their associated four slots of interface, i.e., *activity* (*input*, *output*, *control*, *mechanism*). It is worth mentioning that not all cognitive activities identified from the verbal protocols had all four interfaces. In some cases, some slots had to be left blank. An example of encoded verbal protocols is shown in Appendix B. Finally in the fourth step, the numbers of loops in each type of iteration looping were counted. For example, a subject started her initial design from *analyze problem* and then reached *evaluate*. After performing *evaluate*, the subject used the output of *evaluate* as the input of a subsequent activity of *analyze problem*. At this point, it is counted as one completed PR loop. However, if the subject performed *analyze problem* without using the output from the previous *evaluate* as input, then it would not be counted as a completed loop. For local looping, it is counted as one local loop when any key activity occurs consecutively and the output of the first round is used as an input for the second round.

Coding process is usually carried out by multiple operators in order to maintain the accuracy of the generated code. Due to resource limitations, in this experiment, the code matching was spot checked by a second operator. The spot checker was asked to randomly select a subject's verbal protocol and encode it by the same procedure used by the first operator. The coding results from the two operators were compared. As shown in Table 2, the consistency between the two operators was almost 100% in transcribing, 90% in activity matching, 75% in identifying interfaces, and 95% in counting loops. These results are to be expected because transcribing and counting loops are operator-independent whereas activity matching and interface identification require an operator to interpret the design context. If one operator interprets the design context differently from the other, then the operators will have different encoding results.

4 *Results and discussion*

The protocol demonstrated that *global iteration* loops do exist as shown in the encoding example (Appendix C). Figure 3 presents an example of sketches made by a subject. The figure shows the change made on the idea through iteration loops. In addition to three global iteration loops, the protocol data also illustrated existence of *local iteration* loops within each cognitive activity in our model of conceptual design. However, overall it was hard to observe local iteration loops. It was likely that the local loops occurred too quickly such that some of them might not have been verbalized by the subjects. Furthermore, the inputs, outputs,

Table 2 Consistency between operators

Analysis step	Consistency (%)
Transcribing	100
Activity matching	90
Interface identification	75
Loop counting	95

controls, or mechanisms of several activities were not quite verbally heeded. But they could be identified by combining protocol with video-captured sketches and gestures.

Because the chosen problems have different levels of complexity and require different amounts of time to solve, besides the number of iterations, we also measured iteration in terms of 'the number of iterations per unit amount of time'. For convenience, we use 'loops per 10 min' as the unit measure of iteration frequency. Iteration frequencies, percentages of each type of loops are also considered, which can be simply calculated using the equation below:

$$\text{Percentage of xloop} = \frac{\text{Number of xloop}}{\text{Total number of all loop types}} \times 100\%$$

Note that the numbers of local iteration loops from the experiment are quite low so it does not make much sense to analyze the percentage of each local loop. For this reason, we did not include percentages of local

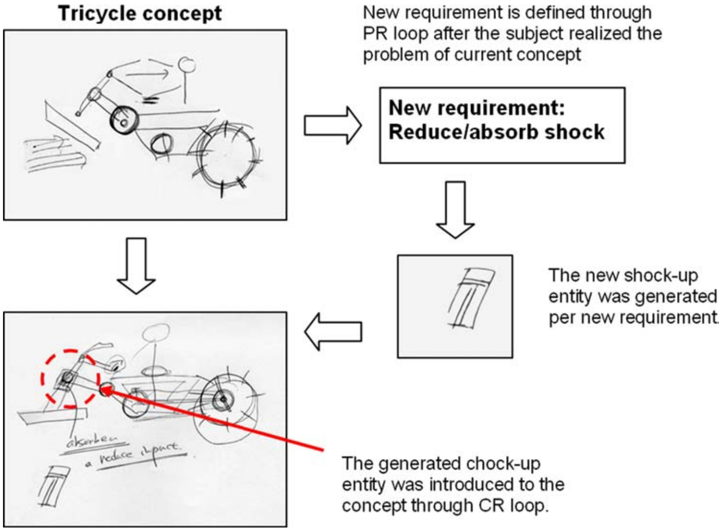

Figure 3 Example of design sketches

loops in our analysis. The average numbers of iterations are presented in Table 3.

4.1 Statistical analysis

Two-way analysis of variance (ANOVA) was performed with the problem type (two levels) and constraint condition (two levels) as independent variables for the following dependent variables: frequency of global loops, number of global loops, percentages of PR loops, percentage of IS loops and percentage of CR loop, frequency of local loops, and number local loops. The level of significance is chosen at 0.05 as a matter of convention. Note that the ANOVA for the percentage of CR loops can be taken as redundancy because it is likely negatively correlated to the percentage of PR and IS loops as the sum of percentages of these loops is always 100. An example of ANOVA using statistical analysis software is presented in Table 5 (Appendix C), which is ANOVA for frequency of global loops. The top portion of the table shows ANOVA table. The center part shows 95% confidence interval. The bottom part presents the estimation of the effects and their coefficients in the first-order regression model. Complete ANOVA tables can be found in Chusilp (2004). The results of ANOVA for each dependent variable will be discussed in Section 4.2–4.7.

In addition, it is necessary to perform residual analysis to validate the assumptions of the test, which are the normality assumption, the equal variance assumption (for estimated effects), and the independence assumption. These assumptions can be checked by inspecting residual plots. The examples of residual plots are presented in Figure 4 (Appendix C). The normality assumption can be checked by inspecting the normality plot of the residuals (Graph A, Figure 4). If the plot shows a straight line pattern, the assumption is satisfied. The equal variance

Table 3 Average numbers of iterations

Independent variables	Non-constrained		Constrained	
	Creative	Routine	Creative	Routine
Frequency of global loops	9.06	4.33	6.38	2.93
Number of global loops	16.13	4.50	14.00	5.25
% of PR loops	32.6	23.9	35.7	31.4
% of IS loops	24.0	8.2	17.9	0.0
% of CR loops	43.4	67.9	46.4	68.6
Frequency of local loops	1.07	1.21	0.76	1.86
Number of local loops	2.00	1.25	1.25	3.38

assumption can be checked by inspecting the plots of residuals versus the factors (Graphs C and D in Figure 4). If the plots show an equal range of residuals at each level of the factors, the assumption is satisfied. The independence assumption can be verified by inspecting the sequence plot (Graph B in Figure 4). If the plot shows no pattern, the assumption is satisfied. From our observation, most patterns are acceptable so ANOVA assumptions were valid.

Because our experiment involves multiple dependent variables, multivariate analysis of variance (MANOVA) needs to be performed to reassure that the significances identified from ANOVAs were not false positives or occurred only by chance. If MANOVA shows significant results, then the ANOVAs computed based on each dependent variable are appropriate. Taking the percentage of CR loops as redundancy, MANOVAs were obtained by using statistical analysis software, as shown in Table 6 in Appendix C. Four tests, which are commonly used, are performed: Wilk's test, Lawley-Hotelling test, Pillai's test, and Roy's largest root test. The top portion of the table shows MANOVA for the problem type effect. The center part shows MANOVA for the constraint condition effect and the bottom portion presents MANOVA for the effect interaction. The results confirm that both effects and their interaction are significant ($p < 0.05$). Therefore, the usage of ANOVAs is acceptable.

4.2 Frequency of global iteration loops

The ANOVA for frequency of global iteration loops shows that both problem type and constraint condition have significant effects on frequency of global iteration loops ($F_{1,28} = 24.69$, $p = 0.000$ for problem types; $F_{1,28} = 6.12$, $p = 0.020$ for constraint conditions) whereas the interaction of the two effects is insignificant.

For the effect of problem type, global iteration loops occurred more frequent in creative design (mean = 7.72) than in routine design (mean = 3.63). This result was expected. Usually, in creative design, designers are not familiar with the problem so they need to iterate their thinking frequently many times before they can generate satisfying and complete concepts. In routine design, on the other hand, designers are familiar with the problem so they tend to spend more time on solving the problem rather than doing iterations. For this reason, routine design involves less frequent iteration than creative design.

For the effect of the constraint condition, global iteration occurred in non-constrained problems (mean = 6.70) more frequently than in constrained problems (mean = 4.66). This result somehow counters our intuition since we thought more constraints may lead to more frequent global iterations to satisfy the constraints. One interpretation of this phenomenon is that to deal with the imposed constraints, designers need to spend more time before moving from one activity to another. Furthermore, adding constraints may limit the design space. As a result, global iteration occurred less frequently. It is, however, considerable that local iteration—i.e., repetitions within each cognitive activity—may occur more frequently in more constrained situations. Further experimental results support this prediction.

We also analyzed the degree of effects of problem types and constraint conditions by fitting a regression model. The result shows that the estimated magnitude of problem type effect (−4.09) is about twice as many as the constraint's effects (−2.04). This result implies that the problem type had stronger effect on the frequency of global iteration than the constraint condition did. Because the analysis was done in *coded* unit, not *natural* unit, the magnitude of difference between the low and high settings of the two factors was treated equally. Therefore, this conclusion can be claimed only to the problems and constraints used in this experiment. Moreover, the two-level factorial design is normally performed for 'screening' purposes. Further experiment and analysis must be carried out if one intends to use the estimated effects for accurate predictions.

4.3 Number of global iteration loops

The ANOVA for number of global iteration loops shows that the effect of problem type is significant ($F_{1,28} = 30.41$, $p = 0.000$), in which the number of iterations in creative design (mean = 15.1) is greater than that of routine design (mean = 4.9), as shown in Table 5. This result supports our discussion on frequency of iterations. On the other hand, the effects of constraint condition and its interaction with problem type are not significant, implying that the numbers of iterations in both constrained and non-constrained conditions are approximately equal.

Together with the result of iteration frequency, it is suggested that although designers iterate less frequently under constrained condition, they finally execute the same amount of iterations to complete the task. As a result, they likely need to spend longer time to finish the task. To confirm this argument, the ANOVA of time spent to complete the task was performed. The result shows that both problem type and constraint condition have a significant effect although the p-value of the constraint condition effect is marginal ($p = 0.038$ for the effect of problem type,

$p = 0.053$ for the effect of constraint condition). Designers spent time on the creative design (mean = 20.4 min) longer than the routine design (mean = 15.0 min) and the constrained problem (mean = 20.2 min) longer than the non-constrained problem (mean = 15.2 min).

4.4 Percentage of each type of global iteration loops

According to the ANOVAs for the percentage of PR, IS, and CR loops, the effect of problem type is significant on every loop percentage ($F_{1,28} = 9.71$, $p = 0.004$ for PR loop; $F_{1,28} = 88.88$, $p = 0.000$ for IS loop; $F_{1,28} = 53.33$, $p = 0.000$ for CR loop). The effect of constraint condition is significant on the percentages of PR loops ($F_{1,28} = 6.08$, $p = 0.020$) and the IS loops ($F_{1,28} = 8.15$, $p = 0.008$) but not CR loop. But the interaction is not significant.

The result shows that both percentages of PR and IS loops in creative design are greater than that in routine design (for creative design, mean = 34.3 for PR loops; mean = 20.6 for IS loop; for routine design, mean = 25.7 for PR loop; mean = 2.8 for IS loop). It is considerable that in routine design, designers normally know a problem well so that they do not need to make much effort to analyze and decompose the problem. Moreover, designers in routine design are likely to compose their designs by moving from one state to another without trying to generate as many new elements as in creative design since they can generate the 'right' elements the first time. As a result, less PR and IS looping is expected in routine design, and the percentage of the CR loop becomes larger. The result of the experiment shows the mean of the percentage of the CR loop is 45.1 in the creative design and 71.5 in the routine design. On the other hand, in creative design, designers are unfamiliar with the design problem and they need to reanalyze the problem iteratively during design. Designers often discover new sub-problems after composing and evaluating intermediate design ideas. Furthermore, in the creative design, it is difficult for designers to generate 'right' elements on the first attempt due to a lack of experience. Frequently, 'right' elements are generated in light of previously generated ideas. Hence, more PR and IS loops are involved in creative design and thus have a bigger share of the total iterations.

For the effect of the constraint condition, the constrained problem involved a greater percentage of PR loops but less percentage of IS loops than the non-constrained problem (for non-constrained problem, mean = 26.6 for PR loop; mean = 14.4 for IS loop; for constrained problem, mean = 33.4 for PR loop; mean = 9.0 for IS loop). It can be considered that imposing constraints makes designers think more iteratively about the problem and do more PR looping. The chance of IS looping is reduced by the imposed constraints. The portion of CR remained unchanged.

We also fitted the regression model to screen the magnitude of effects. For PR loop, the magnitude of the effect of problem type (-8.58) and the effect of constraint condition (6.79) are not much different. But for IS loop, the effect of the problem type (-17.80) is much larger than the constraint condition's (-5.39). This result implies that problem type has stronger effect than constraint condition on the IS loop while both effects are about the same on the PR loop. But again, this conclusion can be made to the problems and constraints used in this experiment only.

4.5 Frequency of local iteration loops

Local iteration occurs when designers iterate within one cognitive activity without involving other ones. More local iteration on one activity implies designer's intention of 'optimizing' the output of that activity. The 'optimization' makes sense only when the designer knows what he/she is looking for and how the local 'output' may contribute to the overall design. It is reasonable to consider that local looping occurs more only when designers are familiar with the overall design problem and know what design results they can expect. This is usually the case of routine design. This consideration is supported by the experiment result. From ANOVA for frequency of local iteration loops, the problem effect is significant on frequency of local loops ($F_{1,28} = 4.87$, $p = 0.036$). It is worth noting that the estimated problem effect on local iteration (0.62) is smaller than its global effect (4.09).

We also consider that besides types of design problems, the number of local loops can depend on constraints imposed on the problem, too. Explicit constraints can make designers locally iterate each activity more frequently to satisfy these constraints before they proceed from the current cognitive activity to another one. So it was expected that local iterations occur more frequently in constrained problem than in non-constrained problem. However, the ANOVA result shows that neither constraint effect nor problem-constraint interaction is significant. Yet, the significance appears at the ANOVA result for the number of local iterations.

4.6 Number of local iteration loops

The ANOVA for the number of location iteration loops shows no significance of main effects but the effect of interaction between problem type and constraint condition ($F_{1,28} = 10.80$, $p = 0.003$). The effect of the interaction is positive, which indicates more local iterations in non-constrained creative design and constrained routine design. On average, the number of local iterations is 2.00 for non-constrained creative design, 1.13 for constrained creative design, 1.25 for non-constrained routine design, and 3.38 for constrained routine design. These numbers show that constrained routine design involves more local iterations and imply that adding constraints has an effect on local iterations only in routine design. This result may be counter intuitive but still explainable. In creative design, designers normally do not have much knowledge of the overall problem. They tend to focus more on generating globally feasible solutions than trying to satisfy constraints. On the other hand, in routine design, designers tend to pay more attention and iterate more to satisfy the constraints since they know they can find feasible solutions. As a result, constraints have less of an effect on local iteration in creative design than in routine design.

The numbers of local iterations were quite low, so making comparisons of the percentage of each type of local iteration loops does not make much sense. For this reason, we did not investigate the percentage of each type of the local iteration loops.

4.7 *Summary of findings*

From the results discussed above, we summarize the findings as follows (see Table 4).

4.7.1 *Effect of problem—creative design versus routine design*

For global iteration loops, the results suggest that creative design involves more frequent global iteration than routine design. Both percentages of PR loops and IS loops in creative design are higher than routine design while the percentage of CR loop in routine design is higher than creative design. For local iteration loops, the results suggest that more routine design yields more frequent local iteration.

4.7.2 *Effect of constraint—non-constrained problem versus constrained problem*

For global iteration loops, the results suggest that constrained problems involve less frequent global iteration than non-constrained problems. In addition, constrained problems yield higher percentage of PR looping but less percentage of IS looping than non-constrained problems. For local iteration loops, constrained problems involve more local iteration than non-constrained problems but *only* in routine design situations.

Table 4 Summary of ANOVAs

Dependent variables		Problem effect	Constraint effect	Interaction
Global loops	Number	Creative > Routine	–	–
	Frequency	Creative > Routine	Non-constrained > Constrained	–
	PR loop %	Creative > Routine	Non-constrained < Constrained	–
	IS loop %	Creative > Routine	Non-constrained > Constrained	–
	CR loop %	Creative < Routine	–	–
Local loops	Number	–	–	Significant
	Frequency	Creative < Routine	–	–

4.7.3 *Effect of interaction between problems and constraints*

The results indicate no significance of the interaction between problem type and constraint condition except for the number of local looping where constrained routine problems may involve more local iteration.

5 *Concluding remarks*

From the proposed cognitive activity model of conceptual design, three distinctive *global iteration* loops among the four major activities are identified, i.e., *problem redefinition loop*, *idea stimulation loop*, and *concept reuse loop*. Besides these *global iteration* loops, there are *local iteration* loops within the cognitive activities. The existence of these mental iteration loops was verified by the protocol data from an experiment study. Deriving the four cognitive activities based on the cognitive processes identified from our previous work (Benami and Jin, 2002) and applying IDEF0 to represent relations between the activities made it possible to develop an effective coding mechanism for protocol analysis and for verifying the iteration loops.

Based on the findings described above, we conclude that the first hypothesis—i.e., *creative design involves more iterations than routine design*—is true, and it was found that the iteration in creative design is made more for analyzing the problem and generating the right ideas whereas in routine design, it is more on reusing ideas. On the other hand, the second hypothesis—i.e., *imposing constraints leads to more iteration*—is at most mixed. Imposing constraints has no effect on the number of global iteration. Constraints make designers iterate more locally only in routine design situations. Furthermore, subjects iterate global loops less frequently in a constrained problem.

Our results indirectly support Adams' transition model of mental iteration (Adams and Atman, 1999; Adams, 2001). While we did not explicitly capture transition behavior, the fact that information was collected and passed between the major cognitive activities implies the existence of transitions. Specifically, the content flows going into the next activity as *controls* and those going out of *evaluate* activity correspond to diagnostic transitions, and those going in as *inputs* can be considered as transformative transitions.

In addition, our research took a complementary perspective in studying the iteration behavior. While existing work investigates how designers with different levels of skill (i.e., freshman versus senior students) perform differently (Adams and Atman, 2000; Costa and Sobek, 2004), our study looks into how designers of the same level of skill perform differently in different design situations. This perspective helps us to understand *what causes designers to iterate differently*. Adding to the understanding that more skillful designers do more iteration (Adams and Atman, 2000; Adams, 2001), our study suggests that it is the need for creativity that calls for more PR and IS iterations; more constraints actually lead to less frequent iteration and the iteration in this case is more for concept reuse.

Furthermore, our finding that PR and IS iterations are needed for more creative (or less routine) design problems is to some extent consistent with the suggestions that problem definition is important for design and that system level problem and solution co-evolution may lead to better design quality (Costa and Sobek, 2004). However, our study further indicates that for routine and constrained design problems designers actually spend more time doing local, rather than system level, iterations.

To summarize, the results obtained from this experiment study suggest that (1) designers' iteration behavior varies in response to design problem types and constraint conditions, and (2) the variation follows certain patterns as indicated in Table 4. In order to provide guidance to designers and insights for tool development, we need to understand how different iteration behaviors may lead to different design performance and how skillful designers 'manage' their design iterations. Our further research investigates the impact of mental iteration loops on design performance (Chusilp and Jin, in press) and elicits how experienced designers iterate differently from novice designers.

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Appendix A. Coding scheme and definitions of terms

This appendix presents coding scheme and definitions of terms that are used in encoding the protocol data.

A.1. Activities

A.1.1. Analyze problem

Code: ANA(p,r,c,e)

Explanation: The designer explores generated requirements/constraints p or evaluation result of entity e, and then generates new requirements or constraints r. c Represents control of activity, which was mostly not presented. *Analyze problem* activity can be identified when a new set of requirements or constraints r appears.

A.1.2. Generate

Code: GEN(e_1,e_2,r,m)

Explanation: The designer generates a new entity e_2 when stimulated by the generated entity e_1. Variable r represents the constraints or requirements that inspire the designer to generate entity e_2. Variable m represents a mechanism of *generate* activity, which is mostly not presented. *Generate* activity can be identified when a new entity e_2 appears.

A.1.3. Compose

Code: COM($e_1 + e_2$,e_3,c,m)

Explanation: The designer combines entity e_1 and e_2, and then transforms them into an evolved entity e_3. Variable c represents control and m represents a mechanism that enables the activity, which are mostly not presented. *Compose* activity can be identified when two or more entities are combined together or the reused entity e_1 is evolved into the entity e_3. In addition, the entity e_2 does not appear if designers just recomposed the idea.

A.1.4. Evaluate

Code: EVA($e_1 + e_2$,p,r,m)

Explanation: The designer evaluates idea e_1 (and e_2 if presented) with constraint or requirement r that yields evaluation statement p. Variable m represents a mechanism that enables the activity, which is mostly not presented. *Evaluate* activity can be identified when entity e_1 (and entity e_2 if presented) are evaluated and the evaluation leads to the result p.

A.2. Iteration loop

A.2.1. Problem redefinition

Class: Global

Code: PR-LOOP

Explanation: A problem redefinition loop occurs when a generated entity makes the designer realize new requirements or constraints. A PR loop can be identified when *analyze problem*, ANA(p,r,c,e) occurs after either *generate*, *compose*, or *evaluate* and entity e matches any output of previous activity or the problem p matches the evaluation the result p from previous *evaluate*.

A.2.2. Idea stimulation

Class: Global

Code: IS-LOOP

Explanation: An idea stimulation loop occurs when a generated entity stimulates the designer to generate a new entity. An IS loop can be identified when *generate*, GEN(e_1,e_2,r,m), occurs after either *compose* or *evaluate*. The stimulating entity e_1 must match any output of previous activity and the generation of the output entity e_2 must be inspired by the input e_1.

A.2.3. Concept reuse loop

Class: Global

Code: CR-LOOP

Explanation: A concept reuse loop occurs when generated entities or a part of generated entities is picked up and reused to compose or evolve an idea. A CR loop can be identified when *Compose*, COM($e_1 + e_2, e_3, c, m$) occurs after *evaluate* activity and the input entity e_1 (and e_2 if presented) must match any output of previous activity.

A.2.4. Analyze problem

Class: Local

Code: A-LOOP

Explanation: An *analyze problem* loop occurs when the designer analyzes the problem that yields new requirements or constraints and these new requirements or constraints make the designer realize other new requirements or constraints immediately without moving into any other activity. This loop can be identified when *analyze problem* activity is repeated and the previous output r is applied as (part of) the input p.

A.2.5. Generate

Class: Local

Code: G-LOOP

Explanation: A *generate* loop occurs when the designer generates an entity and this entity stimulates the designer to generate another new entity. This loop can be identified when *generate* activity is repeated and the previous output e_2 is applied as (part of) the input e_1.

A.2.6. Compose

Class: Local

Code: C-LOOP

Explanation: A compose loop occurs when the designer composes or transforms an entity into the next state of design but he or she recomposes it again because the result is not satisfying. This loop can be identified when compose activity is repeated and the previous output e_3 is applied as (part of) the input e_1 or e_2.

A.2.7. Evaluate

Class: Local

Code: E-LOOP

Explanation: This loop occurs when the designer evaluates the idea and then the evaluation result makes the designer realize another evaluation. It can be identified when evaluate activity is repeated and the previous output p is applied as (part of) the control s.

Appendix B. Coding example

This section illustrates an example of encoding process for verbal protocol analysis in the experiment. We show a fraction of verbal protocol and illustrate how the protocol is encoded.

B.1. Verbal script

'…But it is also self powered. I think it is acceptable. …Ah. Snowboards. Ah, you adapt sketch board to snow board. Maybe it is possible. Ah, as far as self powered. Roller sketches. I guess that is possibility. This makes me thinking of a small ski or I don't know what you call them. But this small ski is very close to ski and self powered. But it not gonna fall in category of going uphill. You can't go uphill because it's really exhausting. It is really not improvement compared to ski. So that is kind of out of question and we won't consider that. My other idea will be those kid carts. They are paddle-powered. There are systems of paddles and chains, like bicycle basically. It is paddles and chains that gonna take you to the back axial. It makes the wheels rotate…'

B.2. Encoding

Note: NP = Not Presented

'But in the sketch board, the problem is that it is a kind of gravity powered. But it is also self powered. I think it is acceptable.'
EVA(sketch board, satisfied sketch board, self-powered, NP)

'Ah. Snowboards. Ah, you adapt sketch board to snow board. Maybe it is possible.'
COM(satisfied sketch boards, snow board, NP, NP)

CR-LOOP

'Ah, as far as self powered. Roller sketches. I guess that is possibility.'
GEN(NP, roller sketches, NP, NP)

'This makes me thinking of a small ski or I don't know what you call them.'
GEN(generated roller sketches, small ski, self powered, NP)

G-LOOP

'But this small ski is very close to ski and self powered. But it not gonna fall in category of going uphill.'
EVA(small ski, not satisfied small ski, go uphill, NP)

'You can't go uphill because it's really exhausting. It is really not improvement compared to ski. So that is kind of out of question and we won't consider that.'
EVA(not satisfied small ski, discarded small ski, NP, NP)

E-Loop

'My other idea will be those kid carts. They are paddle-powered.'
GEN(NP, kid carts + chains + paddles, self powered, NP)

'There are systems of paddles and chains, like bicycle basically. It is paddles and chains that gonna take you to the back axial. It makes the wheels rotate.'
COM(chains + paddles + generated bike, 3-wheel bike, NP, NP)

CR-LOOP

Appendix C. ANOVA and MANOVA tables

This section presents examples of ANOVA and MANOVA tables (Tables 5 and 6) and residual plots (Figure 4) used in our statistical analysis.

Table 5 ANOVA for frequency of global loops

```
Analysis of variance for frequency of global loop
Source        DF       SS       MS       F       P
Problem        1    830.3    830.3   30.41   0.000
Contraint      1      3.8      3.8    0.14   0.713
Interaction    1     16.5     16.5    0.61   0.443
Error         28    764.4     27.3
Total         31   1615.0

                       Individual 95% CI
Problem         Mean   -----+---------+---------+---------+------
-1              15.1                              (------*-----)
 1               4.9   (------*------)
                       -----+---------+---------+---------+------
                          4.0       8.0      12.0      16.0
                       Individual 95% CI
Constraint      Mean   ----+---------+---------+---------+-------
-1              10.3        (-----------------*-----------------)
 1               9.6   (-----------------*-----------------)
                       ----+---------+---------+---------+-------
                         7.5       9.0      10.5      12.0

Estimated effects and coefficients for total (coded units)
Term                  Effect      Coef     SE coef       T      P
Constant                         9.969      0.9236   10.79  0.000
Problem              -10.188    -5.094      0.9236   -5.51  0.000
Constraint            -0.688    -0.344      0.9236   -0.37  0.713
Problem*Constraint     1.437     0.719      0.9236    0.78  0.443
```

Table 6 MANOVA table

```
MANOVA for problem                    s =  1,    m = 2.5,  n = 10.0
Criterion           Test statistic      F          DF          P
Wilk's                   0.15859      16.674      (7,22)      0.000
Lawley-Hotelling         5.30542      16.674      (7,22)      0.000
Pillai's                 0.84141      16.674      (7,22)      0.000
Roy's                    5.30542

MANOVA for Constraint                 s =  1,    m = 2.5,  n = 10.0
Criterion           Test statistic      F          DF          P
Wilk's                   0.44941       3.850      (7,22)      0.007
Lawley-Hotelling         1.22516       3.850      (7,22)      0.007
Pillai's                 0.55059       3.850      (7,22)      0.007
Roy's                    1.22516

MANOVA for interaction                s =  1,    m = 2.5,  n = 10.0
Criterion           Test statistic      F          DF          P
Wilk's                   0.55569       2.513      (7,22)      0.046
Lawley-Hotelling         0.79956       2.513      (7,22)      0.046
Pillai's                 0.44431       2.513      (7,22)      0.046
Roy's                    0.79956
```

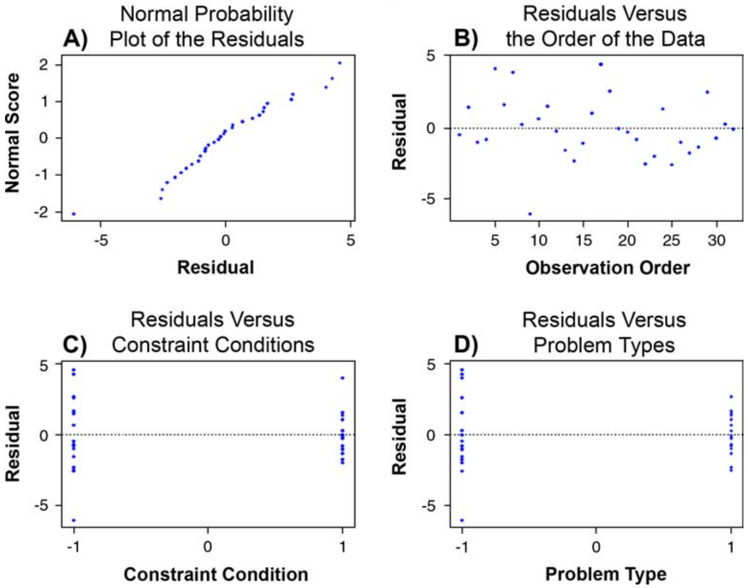

Figure 4 Residual plots for number for global loops