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How to Accumulate Empirical Engineering Knowledge in the Complex Problem-Solving Process for Novice Engineers

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ABSTRACT

Complex problem solving is recognized as an important resource of empirical knowledge accumulation. Learners can acquire and consolidate their empirical knowledge based on practical experience in the complex problem solving. Although many studies on complex problem solving have documented the effects of problem solving on knowledge accumulation, few have addressed the detailed process of empirical knowledge accumulation in the complex problem solving. The purpose of this study is to explore the process of novices' empirical knowledge accumulation in solving complex problem. A multi-stage experiment based on a real-world engineering problem is presented in the study. By means of analysis of the difference between novice and experts, a novel concept of "inflection point" and a novel "four period novices' empirical knowledge accumulation curve" are presented, which can be used to explain the novices' empirical knowledge accumulation process in solving complex problem.

KEYWORDS

Complex Problem Solving, Empirical Knowledge, Knowledge Accumulation, Novice Engineer

1. INTRODUCTION

Complex problem solving is recognized as an important source of expertise accumulation. Learners can acquire and consolidate their empirical knowledge based on practical experience in the complex problem solving (Li et al., 2019, Ozkan, 2013, Wang et al., 2013). Although many studies on complex problem solving have documented the effects of problem solving on learning and knowledge accumulation, few have addressed the detailed process of empirical knowledge accumulation in the complex problem solving (Koo and Ko, 2017, Ahmed, Wallace, & Blessing, 2003, Hwang, Kuo, Chen, & Ho, 2014, Lee, 2010). During the process of complex problem solving, experts take into account and associate the factors which are imperceptible for novices. Accordingly, experts solve problem more accurately and reasonably than novices (liu et al. 2016). In this context, the study aims to explore the process and characteristics of novices' individual empirical knowledge accumulation in complex problem-solving, which can be used to explain how the novices build the individual empirical knowledge structure. Furthermore, our finding will help developing the method to capture and accumulate knowledge faster for novices.

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There are two different levels of knowledge accumulation. The firm-level knowledge accumulation is the foundation for the development of knowledge-based industries. Lai (2009) analyzed the competence of knowledge accumulation in Taiwan's enterprises. Paveena and Kumiko (2014) analyzed the relationship between core technological competence and knowledge accumulation in Japanese functional food firms. other researches attempted to answer the questions involved in individual knowledge accumulation. Jennex (2008) found that the new users to an organization use the KMS differently than the experienced users. Kim (2015) found that learning from actual experiences in software development may be effective for developers to gain new knowledge and increase their skills, no matter whether the developers are novices or experts. Furthermore, many researchers have identified the differences between novices and experts (Ahmed et al. 2005, Deken et al. 2012, Yilmaz et al. 2013). Deken (2012) argued that acquiring information is even more important for novices in problem solving, and found that novices acquire existing knowledge from experts and generate new knowledge together with experts during consultation meetings by means of three consultation processes: information seeking, knowledge creation, and contextual information sharing (Deken et al. 2012). Ozkan (2013) investigated differences in analogical reasoning among first-year, second-year, and fourth-year students and expert architects. The results indicated significant differences among participants. He concluded that experts prefer "mental hops" while first-year students prefer "mental leaps". Second-year and fourth-year students prefer neither "mental leaps" nor "mental hops" but to literally copy the sources (Ozkan et al. 2013). Prior studies have attempted to explain the difference between novices and experts from diverse perspective. However, from the perspective of novice's knowledge processing views, how novices trigger and elicit their experience, and then transfer such experience into their knowledge structure is confused for researcher. Up to now, few studies focus on the novices' empirical knowledge accumulation in the complex problem solving which is the fundamental for empirical knowledge sharing and application.

A multistage longitudinal experiment is presented in our study. In the experiment, an ill-defined complex problem originated from a real-world design task was used to illustrate the novice's empirical knowledge accumulation process (Ifenthaler 2008, Ifenthaler 2011, Kalyuga 2006a, Seel et al. 2008). Totally 95 engineering college students who came from Chinese university participated in the experiment. The transition of individual empirical knowledge was tracked and measured from the initial state to the final state in the multistage longitudinal experiment. The novel concept of "inflection point" and a "four period novices' empirical knowledge accumulation curve" were drawn from the experiment based on the knowledge creation theory and C-K theory.

The paper structure is as follows. The methodology to analyze and measure empirical knowledge accumulation were presented in Section 2. In Section 3, the experiment method and task were explained. In Section 4, the experimental results in detail were introduced and analyzed. Section 5 a thorough discussion about experiment results was given. Conclusion and limitation are then outlined in the last section.

2. METHODOLOGY

2.1 Knowledge Creation Theory and Empirical Knowledge Transfer

The article by Nonaka (1994) in *Organization Science* seminal discussed knowledge creation theory. In his opinion, organizational knowledge creation is the process of making available and amplifying knowledge created by individuals as well as crystallizing and connecting it to an organization's knowledge system (Nonaka 1994, Nonaka et al. 2009). In order to improve organizational knowledge creation, Nonaka introduced an important model named SECI (Socialization, Externalization, Combination, and Internalization), which comprises four modes of practices that convert individuals' tacit knowledge into organization's explicit knowledge assets (Nonaka 1994, Nonaka et al. 2000). Socialization refers to the process involving the conversion of tacit knowledge to tacit knowledge through social interactions, while externalization refers to the process of converting tacit knowledge into explicit knowledge through the process of codification. Combination refers to the process of creation of new explicit knowledge from existing explicit knowledge. Finally, internalization is the process of converting explicit knowledge into tacit knowledge (Alavi et al. 2001, Chang et al. 2012, Linderman et al. 2004, Nonaka 1994). Individual knowledge creation plays a vital role in the organization knowledge creation process (Tsoukas et al. 2001). Individual knowledge structure involves all the information, knowledge, and skills of individuals.). Individual knowledge creation can be employed in particular tasks, or specific problems solving effectively. However, there are some limitations affecting individual's capacity for processing and creating knowledge and skill. The most difficulty one is the acquisition and transition of individual tacit knowledge (Wang, Su, & Hsieh, 2011, Liu 2012, Tohidinia. 2010).

Knowledge tied to the senses, physical experiences, movement skills, intuition, unarticulated mental models, or implicit rules of thumb is tacit (Nonaka et al. 1995, Nonaka et al. 2003). The concept of *tacit knowledge* is a cornerstone in knowledge management. Tacit knowledge is rooted in action, procedures, routines, ideals, commitment, and emotions, which makes tacit knowledge differs from *explicit knowledge*, which is uttered and obtained in drawing and writing. Most of the details about individual experience and skills evolution process, due to their embodiment, are not explicit, which restricts the effectiveness of knowledge transfer from tacit to explicit (Ambrosini et al. 2001, Goldschmidt et al. 2013, Sun et al. 2007).

As a kind of tacit knowledge, empirical knowledge is the specific know-how about the complex problems, which can aid decision-making or problem solving in the specific field. This kind of knowledge does not originate from literature or documents identified as explicit knowledge, but originate from individual experience (Popadiuk et al. 2006). Moreover, empirical knowledge is rooted in human mind and is consequently difficult to be expressed and transferred, and considerably less mobile than more explicit forms (Li et al. 2005, Chen 2010, Abidi et al. 2005, Zhongtu et al. 2006).

2.2 C-K Theory

Generally speaking, problem solving is a creative process based on the transformation of knowledge and information about the actual needs into a solution to fulfill those needs. The knowledge and information have to be transformed into new unknown concepts if solutions based on existing knowledge are not adequate. As such, the distinction between the known (knowledge) and the unknown (concepts) can be made. This distinction determines the core propositions of C-K theory (Hatchuel et al. 2007, Hatchuel et al. 2009, Shai et al. 2009, Zeiler et al. 2012).

C-K theory is a unified design theory and introduced in 2003(Hatchuel et al. 2003). The name "C-K theory" reflects the assumption that design can be modeled as the interplay between two interdependent spaces with different structures and logics: the space of concepts (C) and the space of knowledge (K). Space K contains all established (true) propositions (the available knowledge). K is expandable, such as: the content of K will change over time and definitions of some objects of K may also change. Space C contains concepts which are undecidable propositions in K (neither true nor false in K) about partially unknown objects. Design projects aim to transform undecidable propositions into true propositions in K. The unusual sets of objects defined by concepts is called C-sets. During the design process, C and K are expanded jointly through the action of design operators. Design proceeds by a step-by-step partitioning of C-sets until a partitioned "C-set" becomes a "K-set". This process requires four types of operators: C-C, C-K, K-K and K-C (Hatchuel et al. 2009).

From the perspective of C-K theory, complex problem solving is not only a dynamic mapping process between requirement and solution, but also an expanding process of new objects and new knowledge. Accordingly, the empirical knowledge of person involved in the complex problem solving would expand and increase. That is, through the complex problem solving from first stage to final stage, novices will accumulate new knowledge, and then reconstruct their knowledge structure.

C-K theory is used in our research. The available knowledge of novices represents space K. All representation of a novice's meaning on problem solving is considered to form the space C. The empirical knowledge of a novice is the whole existing knowledge and concept. When a part of concept of a new solution generation in each stage of experiment becomes the true proposition in K(C-K), the other branches of C is concept expansions that do not reach a proposition that belong to K. In addition, new concepts may be triggered from the original or new knowledge drawn from concepts (K-C). When the problem solved, concepts may still remain concepts(C-C) or lead to the creation of new propositions in K (C-K). The novices' empirical knowledge has accumulated within such process.

2.3 Methods for Analysis Measurement

2.3.1 Introduction of Measurement Methods

In this study, the thorny question is how to construct the external representation structures of individual empirical knowledge, and then track the change of individual empirical knowledge from the initial stage to the final stage in the process of problem solving (Abidi et al. 2005, Argote et al. 2011).

Researchers are continually developing new methodologies and techniques to capture key variables associated with individual internal knowledge structures, for example: SMD, MITOCAR and DEEP (Ifenthaler 2008, Ifenthaler et al. 2005, Kalyuga 2006b). Model Inspection Trace of Concepts and Relations (MITOCAR) is based on mental model theory and uses natural language expressions as input data for model re-representation instead of using graphical drawings by the subjects (Maedche et al. 2003). The Dynamic Evaluation of Enhanced Problem-solving (DEEP) methodology is based on a view of learning as becoming more expert-like and more skilled in higher-order causal reasoning and problem solving (Grotzer et al. 2000). The measurement variables are presented based on the above research methods to create a conceptual representation of individual empirical knowledge in our study.

2.3.2 Measurement Index

In this paper, the basic structure of individual empirical knowledge is represented by *concept* and *relation*. The change of core-elements in the knowledge accumulation process is described by Stage Core Concept (SCC) and Stage Core Relation (SCR), the similarity between different stages is measured by Transfer Similarity (TS) and Result Similarity (RS). The detailed description is introduced as following.

1. **Concept and Relation:** Concept and relation are the basic representation of knowledge (Chandrasegaran et al. 2012, Scandura 2007). In this study, the set of concepts and relations indicate the main idea of solution. The numbers of concepts and relations in solution of each stage are selected as a foundational indicator to measure the external individual empirical knowledge.
2. **SCC and SCR:** In order to measure the change of core-elements (concepts and relations) within multistage experiment of empirical knowledge accumulation, a novel concept of stage core-elements is introduced in this paper, which includes two factors: stage core concept (SCC) and stage core relation (SCR).

SCC-*i* (or SCC_i) is defined as such concepts which emerge firstly in stage-*i* and exist to the final stage. For example, assume that five concepts emerge firstly in the second stage, and exist until the final stage. We can say that SCC-*2* is five.

SCR-*i* (or SCR_i) is defined as such relations which emerge firstly in stage-*i* and exist to the final stage. For example, assume that 15 relations emerge firstly in the third stage, and always exist until the final stage. We can say that SCR-3 (or SCR_3) is 15.

3. **TS and RS:** A similarity indicates the degree of similarity between two objects, which is represented by a number between 0 and 1.

Tversky (1977) considers an object as a number of features. The identification of the similarity between two objects is realized by comparing their features (Tversky 1977). The similarity formula takes not only the number of similar features into account, but also the number of different features. Lin (1998) defines similarity with the following three statements: (a) The similarity between A and B is related to their commonality. The more commonality they share, the more similar they are. (b) The similarity between A and B is related to the differences between them. The more differences they have, the less similar they are. (c) The maximum similarity between A and B is reached when A and B are identical, no matter how much commonality they share. Accordingly, the smallest similarity between two objects is given if no common features exist (Lin 1998). In this paper, when the two objects are completely different, the similarity measure is 0. The similarity measure gradually increases with a rise in the number of common features. The similarity measure is 1, when all features are completely similar.

Two types of similarity measures are considered in this paper, including: Transfer Similarity, and Result Similarity. Transfer Similarity indicates the state change of neighboring stage, and Result Similarity is used to measure the state change between some stage and final stage.

Transfer Similarity (TS) indicates the similarity between concepts in *stage i* and those in *stage i+1*.

TS is calculated by formula (1):

$$TS\left(S_i\right) = \frac{f\left(S_i \cap S_{i-1}\right)}{f\left(S_i \cap S_{i-1}\right) + \alpha \cdot f\left(S_i - S_{i-1}\right) + \beta \cdot f\left(S_{i-1} - S_i\right)} \tag{1}$$

S_i: The stage *i*.

$f\left(s_i\right)$: The number of concepts in the stage *i*.

α , β : Weights, used to control the weighting of similar and different features.

Result similarity(RS) indicates the similarity between concepts in *stage i* and those in *stage n (last stage)*.

RS is calculated by formula (2):

$$RS\left(S_i\right) = \frac{f\left(S_i \cap S_n\right)}{f\left(S_i \cap S_n\right) + \alpha \cdot f\left(S_i - S_n\right) + \beta \cdot f\left(S_n - S_i\right)} \tag{2}$$

S_i: The stage *i*.

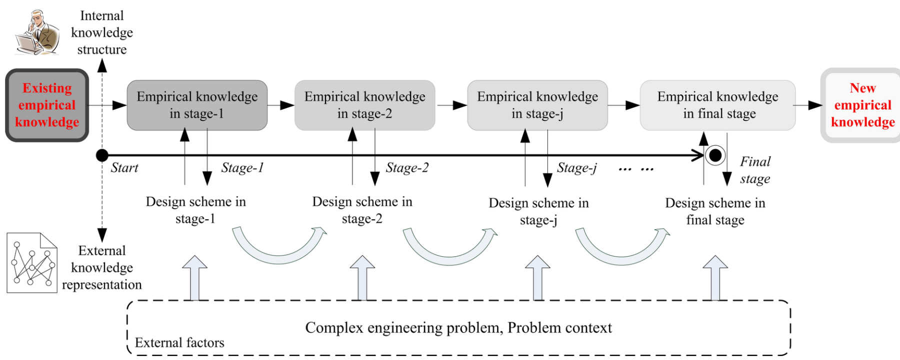
$f\left(s_i\right)$: The number of concepts in the stage *i*.

α , β : Weights, used to control the weighting of similar and different features.

3. EXPERIMENT METHOD

The multi-stage longitudinal experiment is presented in our study. The following sections are structured in the description of the experimental design, experimental task, and participants.

Figure 1. The principle of experimental design



3.1 Experimental Design

Many complex engineering problems are frequently described as ill-defined problems, which are different from well-defined problems and usually exist many possible solutions (Ahmed et al. 2003, Ericsson et al. 1994, Goldschmidt 1997). Solving this kind of complex problem rely more on the individual experience. In turn, individual experience and knowledge would be accumulated by means of complex problem solving.

The principle of the experimental design is shown in Figure 1 and described as following. A multi-stage experiment based on a real-world complex engineering problem is introduced in the study, whose external representation of empirical knowledge is constructed and analyzed. The process of complex engineering problem solving is divided into multiple stages. In each stage, subjects are required to finish the task of this stage and submit the design scheme based on their understanding and recognition about the engineering problems and context in this stage. The completed problem-solving procedure includes the process of empirical knowledge accumulation from have-not to have, and from less to more. The empirical knowledge accumulation can be measured indirectly through the analysis of the change of external knowledge structure (drawing from design scheme). When the complex problem is solved in the final stage, the new knowledge structure is constructed based on the existing empirical knowledge.

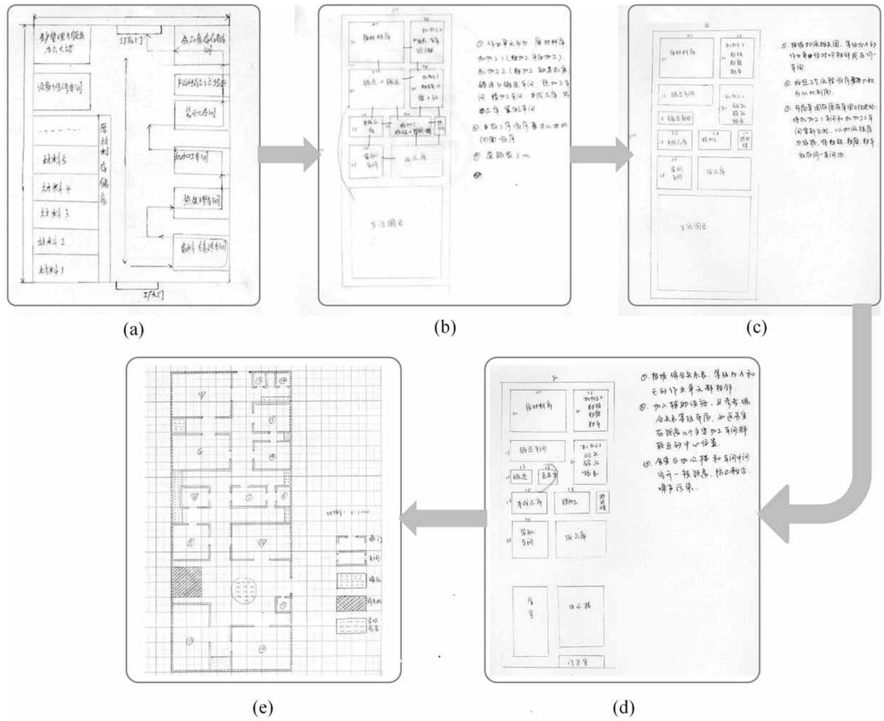
3.2 Experimental Tasks

Based on the investigations in the five manufacturing enterprises (one in Shanghai, two in Jiangsu, and two in Shaanxi, China), we obtain a real-world engineering design cases suited for experiment, and then divide the design task into five stages. The choice of five stages is the same as what has been done in the literature (Burkolter et al. 2012, Liu 2012). Furthermore, pre-experiment is executed by three engineers to evaluate the feasibility of experiment before formal experiment. Our experiment can simulate the real problem-solving procedure in the plant layout, and capture novices' problem solving and empirical knowledge accumulation process.

In the experiment, the background of engineering design problem is a medium-sized manufacturing plant. The product of the plant is all kinds of bending machine. The objective of design is to accomplish a plant layout chart. Novices are required to finish and submit the plant layout design scheme in each stage. The design scheme includes the types and numbers of workshops, relations of workshops, and design draft.

In each stage, the subjects are asked to do the work independently. They are not permitted to discuss with each other in the whole process. Our purpose is to build a suitable environment to facilitate the individual thinking and problem-solving process. In order to ensure that novices have

Figure 2. Draft design in the experiment



(a) Draft design in stage 1 (b) Draft design in stage 2 (c) Draft design in stage 3
(d) Draft design in stage 4 (e) Design solutions in stage 5(final stage)

enough time to recognize and revise their design scheme, each stage lasts about two hours, and only one stage is carried out in one day.

At the beginning of the experiment, subjects are asked to fill a questionnaire for evaluating their capability about layout design. In a 60 min introductory lesson, the experiment content and requirement are explained to all subjects. Then, subjects are required to submit the first stage design scheme in two hours. At intervening measurement points, subjects are asked to submit the design scheme of each stage. In the last stage, subjects are not only required to submit the final design scheme, but also interviewed to answer some questions, such as: what factors are considered in the design process and how to use them, whether they are satisfied with their final design scheme, what are the most difficulties they encounter in the process of design, and how to overcome these difficulties. At last, the score of the design outcome of subjects were rated between 0 and 100 points. Figure2 shows the draft designs from stage-1 to stage-5 (final stage) of one subject.

3.3 Participants

The subjects were fourth year engineering college students from Shanghai Jiao Tong University (in Shanghai) and Shaanxi University of Science and Technology (in Xi'an). Totally 95 students (34 females, 61males) were recruited in our study. They had the same major of industrial engineering, and were familiar with the plant layout procedure. Participants' mean age was 22.1 years. Furthermore, 12 domain experts (two females, ten males) from Shaanxi Automobile Group were recruited as a contrast group, whose mean age was 36.2. Their mean work experience was 12.8 years, with an average number of design projects as 13.3.

Table 1. Measures factors in the experiment

Measure Factors	Meanings (in this Study)	Computation Method	Parameter Explanation
Concept	The specific facilities in design schemes	$N_i = \{n_{ji}\}$, $C_i = \lvert N_i \rvert$	N_i : The set of all facilities in stage *i*. n_i : The No. *j* facility in stage *i*. C_i : The number of facilities in stage *i*.
Relation	The sum of relations of adjacency and separation among facilities	$R_i = \sum_{j=1}^{N_i}\sum_{k=1}^{N_i} \alpha_{jk} r_{jk}$	R_i : The sum of all relations in stage *i*. a_{jk} : The weight value of relation between facility *j* and *k*. $r_{jk} = \begin{cases} 1, \text{ exist relaiton between } j \text{ and } k; \\ 0, \text{ no relation between } j \text{ and } k. \end{cases}$
SCC	The number of specific facilities which exist from some stage to the final stage	$SN_i = N_i \cap N_{i+1} \cap \cdots \cap N_l$, $SCC_i = \lvert SN_i \rvert$	SN_i : The set of SCC in stage *i*. SCC_i : The number of SCC in stage *i*.
SCR	The number of specific relations which exist from some stage to the final stage	$SR_i = R_i \cap R_{i+1} \cap \cdots \cap R_l$, $SCR_i = \lvert SR_i \rvert$	SR_i : The set of SCR in stage *i*. SCR_i : The number of SCR in stage *i*.
TS	the similarity degree of Two neighboring design schemes	$TS(C_i) = Sim(C_{i-1}, C_i)$, $i = 1, 2, \cdots, N.$	See formula (1)
RS	The similarity degree of design schemes between each stage and final stage	$RS(C_i) = Sim(C_i, C_N)$, $i = 1, 2, \cdots N.$	See formula (2)

4. RESULT

In this section, we will first present the descriptive analysis results, and then show the outcomes of in-depth analysis.

4.1 Descriptive Analysis

The meaning and explanation of measurement factors in the experiment are explained in the Table1.

The results of subjects' external knowledge structure measures are described in the Table2. The average facilities design outcome of all novices is M = 13.82(Min =11, Max = 22). The summary of concepts of facilities design scheme increases throughout the five stage, from stage-1 (mean value=11.18, SD=2.17) to stage-5 (mean value=13.82, SD=2.27). Equally, the summary of relations increases from stage-1 to stage-5 (from 34.13(9.18) to 73.06(33.44)). The result indicates the increasing of subject's knowledge after the problem solving.

Additionally, the change of stage core-elements in the external knowledge structures is described by the SCC (Min = 0, Max = 13) and the SCR (Min = 18, Max =144). The SCC of facilities design scheme increases from stage-1(mean value=4.54, SD=2.44) to stage-2(mean value=5.36, SD=3.30), then decreases from stage-2(mean value=5.36, SD=3.30) to final stage (mean value=0.82, SD=0.80). Equally, the SCR also increases in the early stages and decreases in the later stages, which increases

Table 2. The change of subjects' external knowledge structure

		Stage-1	Stage-2	Stage-3	Stage-4	Stage-5
Concept	M(SD)	11.18(2.17)	11.07(2.09)	13.21(2.18)	13.71(2.31)	13.82(2.27)
Relation	M(SD)	34.13(9.18)	42.44(16.05)	65.44(25.55)	71.81(25.90)	73.06(33.44)
SCC	M(SD)	4.54(2.44)	5.36(3.30)	2.14(2.34)	1.07(1.36)	0.82(0.80)
SCR	M(SD)	1.86(0.83)	4.57(2.77)	6.71(3.06)	2.86(3.23)	1.57(1.29)
TS	M(SD)	0(0)*	0.34(0.22)	0.74(0.21)	0.84(0.14)	0.90(0.09)
RS	M(SD)	0.25(0.16)	0.67(0.18)	0.80(0.15)	0.90(0.09)	1(0)**

*in the stage-1, TS=0, **in the stage-5 RS=1.

from stage-1(mean value=1.86, SD=0.83) to stage-3(mean value=6.71, SD=3.06), then decreases from stage-3(mean value=6.71, SD=3.06) to the final stage (mean value=1.57, SD=1.29).

The TS and RS, which describes the concepts similarity between design schemes in the different stages, increases throughout the five measurement stages (Min = 0, Max =1). The TS increases from stage-1(mean value=0, SD=0) to stage-5(mean value=0.90, SD=0.09), The RS also increases from stage-1(mean value=0.25, SD=0.16) to stage-5(mean value=1, SD=0).

4.2 In-Depth Analysis

In order to explore the characteristics of novices' empirical knowledge accumulation, the comparison in the process of knowledge accumulation between novices and experts is necessary. The index of concepts changes, and SCC within multi-stage are measured and compared (Choi et al. 2002).

4.2.1 The Overall Comparison

At first, overall comparison between novices and experts is depicted in the Table3. The indices of comparison includes SCC-1 and Concepts in Final Stage(CFS) of design scheme, The t-test reveals a highly significant level in SCC-1 ($F = 4.113$, $p < 0.01$, confidence interval= (4.47805, 7.61718)) and CFS ($F = 0.339$, $p < 0.01$, confidence interval= (0.62323, 3.90008)). Therefore, there are significant differences between novices and experts from overall comparison. The detailed comparison is shown in the next sections.

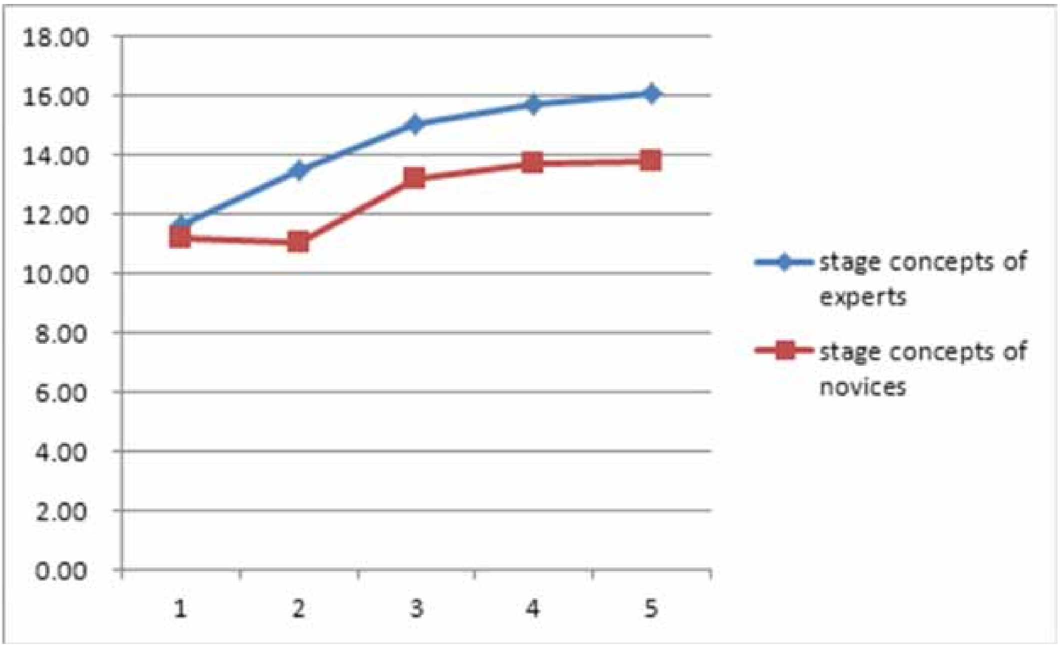
4.2.2 The Comparison of Concept Change

In this section, the change of stage concepts is compared, which means the main idea of design scheme in each stage. Figure3 displays the increase of concepts in each stage for both novices and experts in the experiment. Novices within 5-stage increase concepts number by 2.64 points comparing experts increase concepts number by 4.41 points within 5-stage. Besides the fact that empirical knowledge increases in both groups, the experts achieve considerably higher values (experts: mean value = 14.42, SD= 2.70, novices: mean value = 12.60, SD= 2.52).

Table 3. Overall comparisons of novices and experts

	t	df	Sig. (2-Tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
						Lower	Lower
SCC-1	7.800	105	.000	6.04762	.77533	4.47805	7.61718
CFS	2.795	105	.008	2.26190	.80922	.62373	3.90008

Figure 3. Comparison of concept change



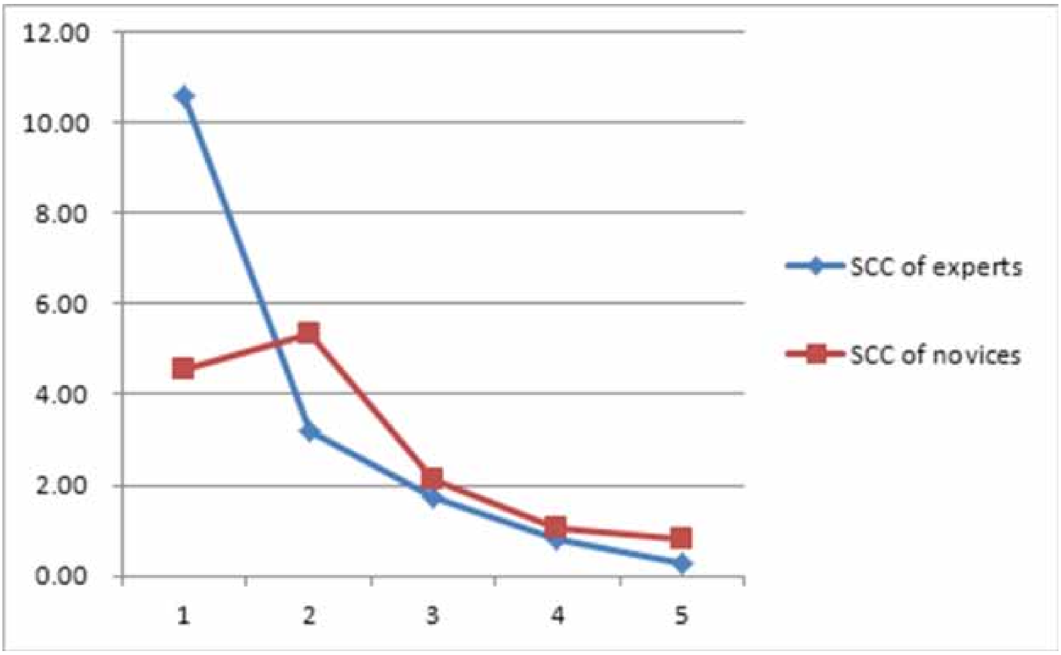
Furthermore, ANOVA is performed to validate the significance between novices and experts

Table 4. ANOVA test results for stage concepts between novices and experts

		Sum of Square	Degree of Freedom	Sum of Mean Square	F-value	p-Value
Stage-1	Between group	2.001	1	2.001	.451	.506
	Within group	168.774	105	4.441		
	Total	170.775	106			
Stage-2	Between group	49.543	1	49.543	10.767	.002*
	Within group	174.857	105	4.602		
	Total	224.400	106			
Stage-3	Between group	29.344	1	29.344	5.700	.022*
	Within group	195.631	105	5.148		
	Total	224.975	106			
Stage-4	Between group	34.811	1	34.811	6.300	.016*
	Within group	209.964	105	5.525		
	Total	244.775	106			
Stage-5	Between group	42.976	1	42.976	7.813	.008*
	Within group	209.024	105	5.501		
	Total	252.000	106			

* $p<0.05$

Figure 4. Comparison of SCC change



(Neyer et al. 2012, Zhang et al. 2012). Table4 depicts that the experts group shows concepts number significantly higher than the novices' group at the 0.05 confidence level. There is significant difference in stage-2($F=10.767$, $p<0.05$), stage-3($F=5.700$, $p<0.05$), stage-4($F=6.300$, $p<0.05$) and stage-5($F=7.813$, $p<0.05$).

4.2.3 The Comparison of SCC Change

In this section, the change of SCC in multi-stages between novices and experts are compared. Figure 4 displays the change of SCC for both novices and experts in the experiment. The SCC of novices decreases by 3.72 points within 5-stage comparing experts' increases by 10.28 points within 5-stage. Besides the fact of SCC decreases in both groups, the SCC of novices decreases slower than those of experts. It is noteworthy that there is a significant Inflection Point (IP) in the process of novices' SCC change. The inflection point means such point which have different change direction on the two sides of point.

Table 5 displays the result of ANOVA test. There are significant differences in Stage-1($F=60.841$, $p<0.001$), stage-2($F=5.738$, $p<0.05$) and stage-5($F=5.120$, $p<0.05$) between novices and experts at the 0.05 confidence level.

Therefore, there is significant difference between novices and experts in the empirical knowledge accumulation process based on the results of the change of stage concepts and SCC.

5. DISCUSSION

We have firstly confirmed the existing of the empirical knowledge accumulation of novices in the process of complex problem solving based on the experiment results and above analysis. The conclusion is in line with the knowledge creation theory and C-K theory (Nonaka 1994, Hatchuel et al. 2009). In addition, our finding confirms the significant difference between novices and experts of empirical knowledge accumulation in complex problem solving, which is according with the prior

Table 5. ANOVA test results for SCC change between novices and experts

		Sum of Square	Degree of Freedom	Sum of Mean Square	F-Value	p-Value
SCC-1	Between group	307.219	1	307.219	60.841	.000**
	Within group	191.881	105	5.049		
	Total	499.100	106			
SCC-2	Between group	50.030	1	50.030	5.738	.022*
	Within group	331.345	105	8.720		
	Total	381.375	106			
SCC-3	Between group	2.630	1	2.630	.560	.459
	Within group	178.345	105	4.693		
	Total	180.975	106			
SCC-4	Between group	1.376	1	1.376	.864	.358
	Within group	60.524	105	1.593		
	Total	61.900	106			
SCC-5	Between group	2.743	1	2.743	5.120	.029*
	Within group	20.357	105	.536		
	Total	23.100	106			

*P<0.05
**p<0.001

studies (Ahmed et al. 2003, Ozkan et al. 2013). However, we have found some interesting phenomena that are not mentioned in previous literatures. In this section, we will discuss these phenomena in order to acquire some others valuable results.

5.1 Discussion on the Change of Core Elements

5.1.1 Change of Stage Core-Elements

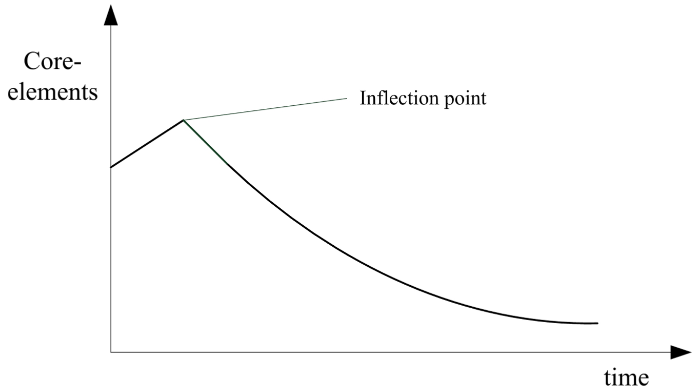
From the change of SCC and SCR as shown in Table6, we find an interesting phenomenon in the novices' empirical knowledge accumulation process, in which the value of SCC increases from stage-1 to stage-2 and then decreases from stage-2 to stage-5. Equally, the value of SCR increases from stage-1 to stage-3 and then decreases from stage-3 to stage-5.

We attempt to explain the phenomenon as follows. Core elements are such items which emerge in some stage and last to the final stage in the process of problem solving. In the experiment, the SCC-1 means such concepts which emerge in the initial design scheme and lasting to final design

Table 6. The change of core elements

Core Elements		Stage-1	Stage-2	Stage-3	Stage-4	Stage-5
SCC	Mean value	4.54	5.36	2.14	1.07	0.82
	SD	2.44	3.30	2.34	1.36	0.80
SCR	Mean value	1.86	4.57	6.71	2.86	1.57
	SD	0.83	2.77	3.06	3.23	1.29

Figure 5. The curve of core-elements' change



scheme. That is to say, SCC-1 indicates those concepts which belong to original empirical knowledge structures of novices. These concepts are triggered and used when novices begin their design tasks in stage-1. In further, the phenomenon of SCC-2 greater than SCC-1 implies that the new concepts and new knowledge innovated in stage-2 is more than those in stage-1. The increasing of SCC from stage-1 to stage-2 indicates that the design scheme of stage-1 is modified a lot in stage-2 by novices, and more concepts of stage-2 are kept in the final design solution than those of stage-1. SCC-3 is less than SCC-2 in the experiment, which means that the design schemes of stage-2 are repaired a little in stage-3 by novices. Equally, SCC-4 and SCC-5 decrease gradually, which indicates that concepts are repaired less and less in the latter stages. Accordingly, we can draw a conclusion that a lot of repairing work of design scheme is finished in the earlier stages from the comparison of SCC-1 to SCC-5. That means more new concepts emergence and new knowledge transfer accomplish in the earlier stages. Furthermore, we can obtain similar result from analysis of the change of SCR.

5.1.2 Analysis of Inflection Point

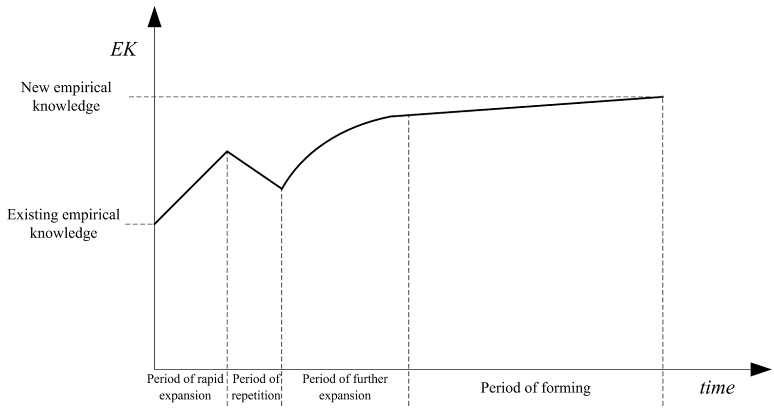
The analysis in above section indicates that the process of novices' empirical knowledge accumulation is not linear. The existing of unique characteristic in the process of novices' empirical knowledge accumulation is proved by the experimental results. That is inflection point, which is the most important finding in our study. In the experiment, the inflection point emerges in the place of SCC-2 and SCR-3. The features of inflection point can be summarized as follow:

1. The inflection point is the unique characteristic of novices' empirical knowledge evolution, which is confirmed in Figure 4. The inflection points existing in the process of novices' problem solving is not found in the process of experts.
2. The emergence of inflection point is in the early stage of novices' empirical knowledge accumulation process, which is confirmed by the change of SCC and SCR.
3. The inflection point is the boundary point of empirical knowledge accumulation process. Core-elements increase fast before the inflection point. However, they decrease slowly after the inflection point as shown in Figure 5.

Our finding was confirmed by the interviews with subjects after the experiment. 60 percent of subjects admitted that they made major revision on their design schemes in the second stage, and 20 percent of subjects made major revision on their design schemes in the third stage.

The research findings are consistent with the existing literature (Ahmed et al. 2000, Ahmed et al. 2003, Sivaloganathan et al. 2013, Snider et al. 2013). The results imply that the novices tend to use a

Figure 6. The process curve of novices' empirical knowledge accumulation



particular pattern of trial and error in the problem solving, which leads to the noticeable fluctuation on the empirical knowledge accumulation in the early stages.

5.1.3 Core-Elements Change Curve

Based on the above analysis, a novel core-elements change curve of novices' empirical knowledge accumulation is presented. The curve is shown in Figure 5, in which the number of core-elements increases fast in the early stage, and it decreases in the later stage after the inflection point (the top peak in Figure 5). The stage including inflection point, for example: SCC-2 or SCR-3 in the experiment has more influence on the final result than other stages. In the problem-solving process, novices would do minor changes and innovation after the inflection point. Equally, the results of empirical knowledge accumulation are more and more stable.

5.2 Discussion of Accumulation Stage

Due to the existence of inflection point, the empirical knowledge accumulation process of novices is more complex than that of experts. A novel empirical knowledge accumulation curve of novices is presented based on the result of experiment. The curve is shown in Figure 6. The curve incorporates four periods: period of rapid expansion, period of repetition, period of further expansion, and period of forming. The following is the explanation of each period:

1. **Period of Rapid Expansion:** In the beginning stage of problem solving, novices accumulate empirical knowledge rapidly (the evidence in experiment is the fast increasing of SCC, SCR and concepts in the beginning stage). The phenomenon is supported by Ahmed (2000,2003), who presented that novices tend to use problem solving pattern of trial and error, not problem-solving strategies, which are the particular pattern of experienced designers (Ahmed et al. 2000, Ahmed et al. 2003). Therefore, through trial-error and scattered thinking, novices analyze the complex problems and scenarios combining their own existing knowledge, and then generate the problem scheme, with plenty of new concept and knowledge enter the schemes.
2. **Period of Repetition(Self-Correction):** This period is following the period of rapid expansion. With the re-examine about the problem and scheme from initial stage, novices may recognize the mistakes they make in the beginning period. Accordingly, in this period, novices inspect the problem scheme of the first stage, and then dispose incorrect concept and persist correct concept and knowledge (the evidence in experiment is the emerging of inflection point). This is accord

with C-K theory, which presents the potential concept may lead to a revision of the identity of existing knowledge. The concept allows for such potential changes in the identities of objects in knowledge space (Hatchuel et al. 2009).

3. **Period of Further Expansion:** After the inspection of the problems and solution in the second period, novices recognize the problem more deeply. Accordingly, novices' empirical knowledge accumulation enters a rapid expansion period (the evidence in experiment is the fast increasing of concepts after the inflection point).
4. **Period of Forming:** At the last period, the solution will be completed. Accordingly, novices' empirical knowledge accumulation on the problems solving is tend to stable and mature, and only seldom new concept and knowledge enter the empirical knowledge structure of novices. Up to now, novices finish the process of empirical knowledge accumulation based on the complex problem solving (the evidence in the experiment is the slow increasing of concept in the last stage, and the number of SCC and SCR are tending to zero).

The four periods of novices' empirical knowledge accumulation curve are accord with knowledge creation theory. In the model of SCIE, Nonaka presented that knowledge is created in the dynamic spiral process which goes through two seemingly antithetical concepts (Nonaka et al. 2000).

6. CONCLUSION AND LIMITATION

This study is one of the first attempts to employ existing knowledge creation theory and C-K theory to explore the characteristics of novices' empirical knowledge accumulation process. Based on the longitudinal study and a novel experiment originated from real world complex engineering problem, the important phenomenon and characteristics of the empirical knowledge accumulation process are found in our study. An important concept of inflection points and a novel "four period novices' empirical knowledge accumulation curve" are presented based on the experiment. Our finding extends the study of Ahmed (2003) and Zeiler (2012) by integrating the C-K theory and multi-factors measurement methods. This is an important contribution of this study because few prior researches (Ahmed et al.2003, Zeiler et al.2012).

The results can be used to describe and explain the novices' empirical knowledge accumulation process in solving complex problem. Our findings suggest that the empirical knowledge accumulation process is not linear. The different knowledge accumulation periods should be treated use different methods. For example, in the period of further expansion, the quantity of new knowledge is less than them in the period of repetition. However, the quality of new knowledge is higher. Therefore, the evidence found from this study helps us to identify the critical areas in which novices fail to perform a good review, and may serve to develop approaches to overcome such limitations. We believe that our finding based on the knowledge creation theory and real-world complex problem gives novices some useful support for the complex problems they have to face in practice. The long-term aim of this research is to develop a way to support novices acquire and accumulate empirical knowledge easier.

There are some limitations in our study, which provide directions for future study. First, our study focused on exploring the process of novices' empirical knowledge accumulation from the comparison between novices and experts. The question of what factors cause the difference between novices and experts needs further study. Second, our research confirms that inflection point is not only the most notable characteristic of novices' empirical knowledge accumulation process, but also the important difference between novices and experienced designers. Therefore, how to reduce and eliminate the negative effects caused by the inflection point is the focus of our future research.

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