A model of learning in design derived from a protocol analysis

Siang Kok Sim* and Alex H B Duffy+

*School of Mechanical and Production Engineering,
Nanyang Technological University,
Nanyang Avenue, Singapore 639798,
Republic of Singapore.

+CAD Centre,
University of Strathclyde,
75 Montrose Street, Glasgow G1 1 XJ,
United Kingdom

1 Introduction

The aim of this paper is to evaluate and evolve a model of learning in design [1] through the results of a protocol analysis. The protocol recording of a designer at work provides an avenue by which the phenomenon of learning in design could be studied. Therefore, by comparing the results of the protocol analysis of a designer at work in relation to the proposed model, one is able to propose modifications to the model of learning in design. Hence the evaluation through the protocol analysis has resulted in an evolved model.

2 Protocol analysis

Protocol analysis has been used to evaluate a case study of a designer at work. The purpose of the protocol analysis was to evaluate and/or evolve the original model of learning in design. The original model of learning has been expressed in the formalisms of a design activity and a learning activity. This is based on the assumption that the phenomenon of learning in design can be dichotomised into design and learning activities. The formalism of a design activity was hypothesised to reflect what the elements of a design activity are, and how these elements interact [1]. Similarly the formalism of a learning activity was hypothesised to reflect what the elements of a learning activity are, and how these elements interact [2]. Sim and Duffy [3] postulated that the design activity and learning activity interact in three manners; epistemically, teleologically and temporally.

2.1 Elements of a design activity

The first hypothesis concerns the existence of elements of a design activity. The evaluation shows, using sequential verbalisation [4], that the elements of a particular design activity identified are input knowledge, design goal and output knowledge.

An ontology of design activities was derived through a comprehensive though not exhaustive literature survey of the corpus of knowledge reported in journals, books and conference proceedings of design, cognitive science, machine learning and machine learning in design. Table 1 below shows a comparison between the ontology of design activities proposed in the original model and those identified in the protocol analysis (* design activities identified in the protocol analysis are marked by ✓). For fuller descriptions see [1].

Table 1: Design activities identified in the protocol analysis

Design definition activities	*	Design evaluation activities	*	Design management activities	*
Abstracting		Modelling		Constraining	✓
Association	✓	Analysing	✓	Exploring	✓
Decomposing	✓	Testing/Experimenting		Identifying	✓
Defining	✓	Evaluating	✓	Information gathering	✓
Generating	✓	Decision making	✓	Planning	
Standardising	✓	Determining	✓	Prioritising	✓
Structuring/Configuring	✓	Verifying		Resolving	✓
Synthesisin	✓			Scheduling	
				Selecting	✓
				Searching	✓

The comparison shows that some of the design activities are not identified in the protocol recorded. The design activities not identified are abstracting, modelling, testing/experimenting and verifying, planning and scheduling. This may be due to the fact that the video recording was taken of a designer engaged in a particular type of design task; in this case that of general arrangement of a ship. Unlike conceptual design in which abstracting of ideas or concepts are used in generating designs, for general arrangement or configuration design, the systems, sub-systems and design objects have been pre-determined. So the preoccupation of the design task was how to achieve an optimal layout or arrangement that can satisfy all the design requirements. Hence this may be the reason that design activities such as abstracting have not been identified in the protocol recording of this case study. Nevertheless, these activities have been identified in other protocol recordings. For example, Cross and Cross [5] identify the activity, planning in the Delft's protocol recording [6] among other design activities.

2.2 Elements of a learning activity

In order to identify the elements of a learning activity, the segments of the protocol in which learning occurs must be identified. The protocol analysis reveals that it is difficult to identify when learning has taken place. In most cases where learning activities have been identified, the occurrence of learning is inferred based on segments of the protocol in which there was application of past design knowledge (i.e. design reuse) in a particular design activity. These instances suggest the learning of design knowledge but it is often difficult to infer with certainty whether learning had occurred in-situ or retrospectively after the design task.

Learning is suggested to occur in design activities in which it is inferred that knowledge change has taken place. In such instances it is inferred that learning has occurred in-situ. This is illustrated by an instance in which it is possible to infer that learning has occurred in-situ. In generating various concepts of engine room layout, for one particular concept generated involving six propellers connected to ‘U-drive’ gearboxes, reference was made to the knowledge learnt in the first concept generated. In that concept the evaluation result was that it was not possible to accommodate six propellers involving six engines. The evaluation result was applied to the concept in which propellers are coupled to ‘U-drive’ gearboxes. This clearly shows an example of in-situ learning of the result of evaluation of the first concept. This example shows that although the designer did not state explicitly that he/she was learning during the design process, it serves as evidence that learning had taken place though implicitly (i.e., without the designer verbalising it) after evaluating the first concept. This example also serves to illustrate that input knowledge to the design activity of generating a concept would seem to be the same input knowledge to the learning activity that occurred in-situ.

Inferring learning goals

In instances where it was inferred that learning could have taken place (retrospectively or in-situ) through the application of knowledge learning goals were inferred from the context of the segment of the protocol. Each learning goal was inferred with respect to the design goal identified in that segment.

Knowledge transformer

The protocol analysis shows that there was no explicit way of identifying knowledge transformers (an activity that transforms knowledge). In fact, the knowledge transformer is inferred by studying the knowledge change in a design activity and the knowledge transformer is then inferred from the nature of the knowledge change. Although care was taken to interpret or infer the knowledge change in each segment of protocol correctly, one cannot claim absolute objectivity in the interpretation.

Table 2 shows a comparison of the knowledge transformers postulated in a learning activity and those inferred through the protocol analysis. The comparison suggests that protocol analysis provides evidence in support of the repertoire of knowledge transformers in the proposed model of learning in design, except for one pair of knowledge transformers (i.e. sorting/unsorting) that was identified in the protocol analysis.

Table 2: A comparison of the knowledge transformers postulated in the model of learning and those inferred in the protocol analysis.

Knowledge Transformers	Model of learning in design	Inferred in the protocol analysis
Abstraction /Detailing		
Association/Disassociation		
Derivations/Randomisation		
Explanation /Discovery		
Generalisation /Specialisation		
Group Rationalisation or Clustering /Decomposition		
Similarity comparison/Dissimilarity comparison		
Sorting/Unsorting		

Knowledge of knowledge transformers

The protocol analysis reveals that there may exist a mapping between design activities and knowledge transformers or vice versa. This revelation implies that the design agent should have knowledge of the knowledge transformers (i.e. meta-knowledge) by which appropriate knowledge transformer(s) can be selected for a particular design activity.

Temporal Triggers of learning

The three types temporal learning triggers (i.e. provisional learning trigger (T_p), in-situ trigger (T_i) and retrospective trigger (T_r)) have been inferred to exist through the protocol analysis of the case study.

Output knowledge and Accumulation of Output knowledge

From the protocol analysis, it can be seen that as a result of the knowledge change, there are numerous types of output knowledge. Learning occurs when the output knowledge is recorded in the memory of an agent. For the purpose of classification, the tentative list proposed by Grecu and Brown [7] was used to classify the types of output knowledge learned with respect to three categories of design activities. The protocol analysis reveals that for each design activity there is a transformation of input knowledge into specific output knowledge through the knowledge transformer. At the end of the design task, it is conceivable that there would be an accumulation of various types of specific output knowledge. This suggests that there is a link between the nature of the design activity, the knowledge transformer and the specific output knowledge.

3 The evolution of the model of learning in design

The protocol analysis has been used to study the phenomenon and to evaluate the original model of learning in design [1]. The protocol analysis has revealed several aspects of the model that were not envisaged in the original formulation. Hence from the results of the evaluation of protocol analysis, the findings would contribute towards formulating an evolved model of learning in design. From the study of the interactions between the design and learning activities, it can be shown that these activities are inextricably linked at the epistemic level, teleological level and temporally. This implies that the original assumption of decomposing the two cognitive activities for the purpose of simplification of the protocol analysis may not be valid. Furthermore the learning goals and design goals mutually influence one another depending on the nature of the design activities. There appears to be a mapping between the design activities and knowledge transformers. There is therefore a need to depict mapping between the knowledge of design activities and the knowledge of knowledge transformers in the model. Hence arising from the evaluations discussed in Section 2, there is a need to propose an evolved model of learning in design.

3.1 Interaction between design and learning activities

Through the protocol analysis, it has been shown that these activities interact through three links, the epistemic link, the temporal link and the teleological link.

3.1.1 The epistemic link

The protocol analysis reveals that knowledge change does occur in a design activity and that this knowledge change can be attributed to certain knowledge transformers should learning take place. Where learning occurs, this inference from the protocol analysis suggests that there is an inextricable link between the input knowledge to the design activity and the learning activity and the output knowledge of the design activity and that of the learning activity. The element that links the input knowledge and that of the output knowledge is the knowledge transformer and the resulting knowledge change is in the context of a specific design activity. That there is a relationship between a design activity and learning activity is not depicted in the original model of learning in design.

The original model of learning in design was not able to predict, for a given design activity, what are the likely knowledge transformers for the knowledge change to occur; that is, what is the mapping between design activities and knowledge transformers and vice versa. From the knowledge transformers inferred in the protocol analysis, it is observed that there was a mapping between the nature of design activities and the knowledge transformers. Table 3 presents the mapping between knowledge transformers and the three categories of design activities (i.e. design definition activities, design evaluation activities and design management activities).

From Table 3, it can be observed that for design definition activities, except for the two pairs of knowledge transformers *Explanation/Discovery* and *Sorting/Unsorting*, the knowledge transformers have been inferred in these activities. This is conceivable as the nature of design definition activities is such that the knowledge transformers involved will be those that promote an increase in definitional knowledge of the design rather than knowledge transformers such as *Explanation/Discovery* and *Sorting/Unsorting*. For design evaluation activities, except for the two pairs of knowledge transformers, *Group rationalisation/Decomposition* and *Sorting/Unsorting*, the knowledge transformers have been inferred in these activities. These two pairs of knowledge transformers are less likely to be responsible for the knowledge increment relating to design evaluation activities. For design management activities, the pair of knowledge transformers, *Group rationalisation/Decomposition* has not been inferred in these activities.

The mapping between knowledge transformers and design activities suggests that there is meta-knowledge that determines when appropriate knowledge transformers should be applied in specific design activities; that is, the meta-knowledge refers to the knowledge of knowledge transformers.

Figure 1 shows the relationship between a specific design activity, A_d, and knowledge transformer, K_t, and its relationship to mapping knowledge of knowledge transformers K_k and the repertoire of design activities A_{dk} stored in memory.

Table 3: Mapping between knowledge transformers and categories of design activities inferred in the protocol analysis.

Knowledge Transformers	Design definition activities	Design evaluation activities	Design management activities
Abstraction/Detailing	Defining	Determining, Evaluation	Information gathering, Selecting, Searching
Association/ Disassociation	Associating, Defining, Structuring/configuring, Synthesising	Decision-making, Determining	Identifying
Derivation/ Randomisation	Generating,	Analysing, Determining, Decision-making, Evaluation.	Constraining, Exploring, Identifying
Explanation/Discovery	Not inferred.	Decision-making	Constraining, Exploring, Identifying, Resolving
Generalisation/ Specialisation	Defining	Determining	Constraining
Group Rationalisation/ Decomposition	Decomposing	Not inferred.	Not inferred.
Similarity comparison/ Dissimilarity comparision	Generating, Standardising	Analysing, Evaluation	Identifying
Sorting/Unsorting	Not inferred.	Not inferred.	Prioritising

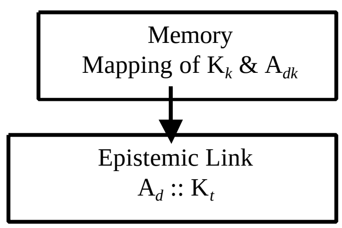

Figure 1: The mapping between knowledge transformers and design activities

3.1.2 The teleological link

The study of the interaction between the design goal, G_d, and learning goal, G_l, shows that the design goal can precede the learning goal or vice versa. The protocol study reveals that for design activities such as configuring, defining, standardising, identifying, evaluation and decision-making, the designer verbalised the learning goals before the design goals.

It is also shown in the protocol analysis in cases where there is application of knowledge learnt, it is often as a result of failure avoidance or novelty driven [2]. Where there is application of knowledge to a design situation, it implies that there is a triggering of the learning process in the first place. Hence learning occurs in these design situations because of these learning triggers. These can be considered as *rationale* learning triggers, T_{lw}; that is, these triggers denote the reason that triggers learning. Hence Figure 2a shows the *rationale* learning trigger, T_{lw} that activates the learning goal, which precedes the design goal. This suggests that the rational learning triggers the learning activity that precedes the design activity (i.e. that knowledge has been learnt either retrospectively or provisionally before application in the current design situation).

For activities such as associating, defining, generating, constraining and exploring, the designer verbalised the design goals before the learning goals. In Figure 2b, the design goal, G_d, precedes the learning goal, G_l, (i.e. $G_d \rightarrow G_l$) in that for certain design situations, the design activities are not necessarily influenced by the learning goal. Learning may occur during the design activity so that the knowledge gained can be applied in a similar design situation.

The protocol analysis supports the hypothesis that the design goal and learning goal are teleologically linked for it suggests that both can mutually influence one another in activating the learning activity. In order to generalise the findings, it is necessary to conduct more protocol analyses of different design tasks (e.g. conceptual design, detail design in similar and other engineering domains). However, the findings suggest that the nature of the interaction between the design goal and the learning goal is dependent on the nature of the design activity.

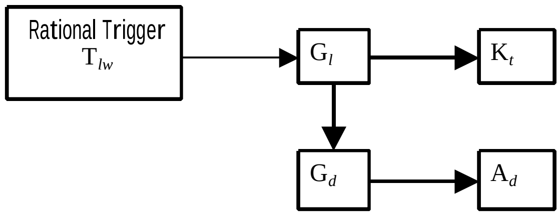

Figure 2a: Learning goal precedes design goal

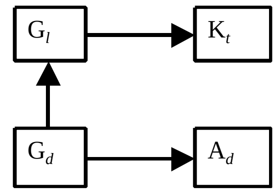

Figure 2b: Design goal precedes learning goal

3.1.3 The temporal link

The evaluation of the protocol analysis shows that the design activity and learning activity are temporally linked (i.e. retrospectively, in-situ and provisionally; see Figure 3) [2]. Hence the protocol analysis supports the hypothesis that the design activity and learning activity are temporally linked as was postulated in the original model.

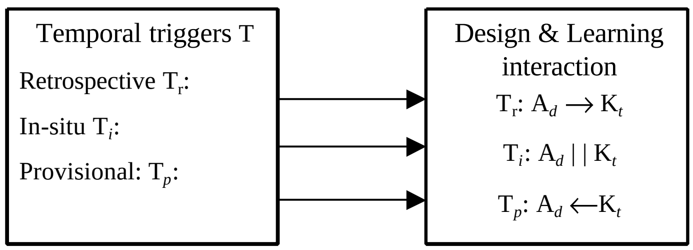

Figure 3: Temporal learning triggers activating the design and learning activities.

3.2 The evolved model of learning in design

The evolved model of learning in design (named as ModelLinD) is shown in Figure 4. The evolved model is derived from the modifications to the original model [3] arising from the protocol evaluation.

In the evolved model, the interactions between a design activity and learning activity are clearly shown. For the purpose of deriving formalisms for the design and learning activities and the analysis of protocol recording, the phenomenon of learning in design was dichotomised into two distinct cognitive activities. From the protocol analysis, it was observed in segments of the protocol in which in-situ learning and retrospective learning were inferred that the input knowledge into a design activity was the same input knowledge into the learning activity. Hence, there is no distinction between the input knowledge to the design activity and learning activity depicted in the evolved model.

There is a mapping between knowledge of design activities and knowledge of knowledge transformers ($A_d :: K_t$) showing the inextricable link between the design and learning activities at the epistemic level.

Depending on the type of the design activity (Table 1), there are two possible ways by which design and learning goals interact with one another; this depicts the inextricable link at the teleological level. Firstly, the learning goal (which is triggered by the rationale learning trigger, T_{lw}) precedes the design goal (i.e. $T_{lw,} \longrightarrow G_l \longrightarrow G_d$). Secondly, the design goal precedes the learning goal (i.e. $G_d \longrightarrow G_l$). Depending on the learning goal, the output knowledge may act as the reason for further learning activity. Hence, the feedback of output knowledge as input into the learning activity depicts the iterative nature of the learning process.

For many of the design activities, the knowledge change which is a pre-requisite to learning occurrs in-situ or provisionally. But for certain types of experiential knowledge (e.g. trends of relationships among design parameters, knowledge of cause of failure in design) learning of the knowledge is of utility value if it is learnt in retrospect. Hence there are three types of temporal learning triggers (i.e. retrospective trigger (T_r), in-situ trigger (T_i) and provisional trigger (T_p)) shown in the model. For the retrospective learning trigger, the learning activity succeeds the design activity ($A_d \longrightarrow K_t$). For the provisional learning trigger, the learning activity precedes the design activity ($A_l \longrightarrow A_d$). For the in-situ learning trigger, the learning activity occurs concurrently with the design activity ($A_d \,||\, K_t$).

The output knowledge, O_k, from each learning situation is stored in the memory as experiential design knowledge that is basically an accumulation of output knowledge from the design task(s). Within the memory is also the knowledge of knowledge transformers, K_k and the mapping between knowledge of knowledge transformers, K_k and the repertoire of design activities, A_{dk}.

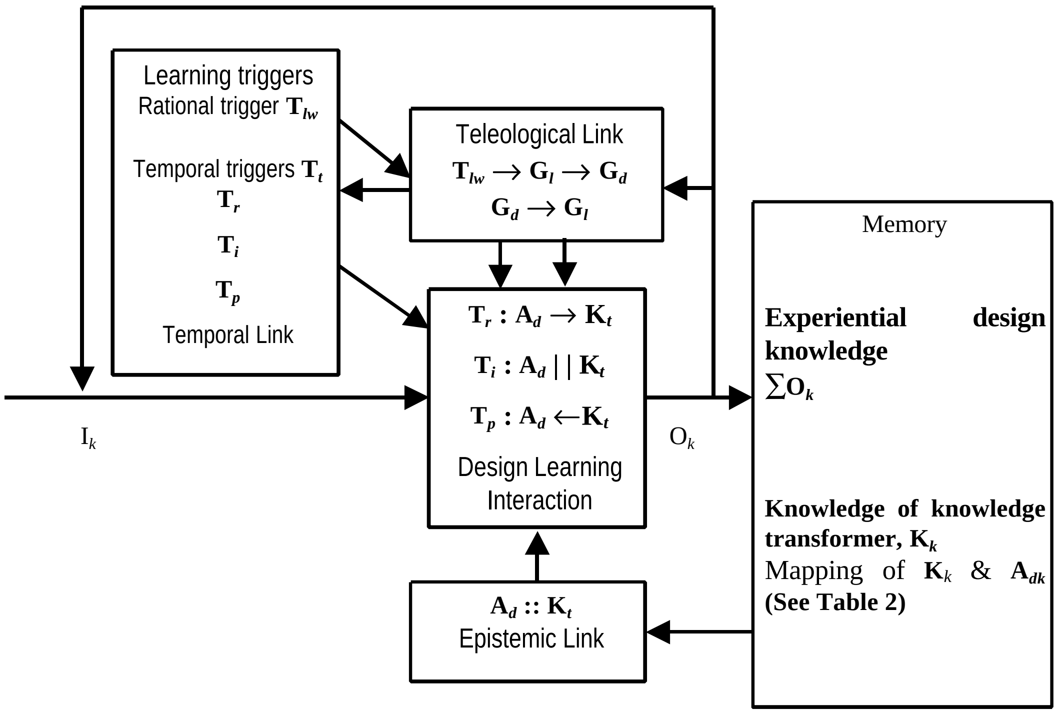

Figure 4: An evolved model of learning in design, Model-LinD

4 Conclusion

This paper has presented an attempt at modelling learning in design. A protocol analysis has been used to evolve an earlier model [3]. The analysis reveals that it is difficult to identify when learning has taken place as it is a cognitive activity and as such has been inferred based on segments of the protocol. It is often difficult to infer with certainty whether learning had occurred in-situ or retrospectively after the design task. While considerably more analysis and research work is required the evolved model is one step towards the development and better understanding of a model of learning in design.

References

[1] Sim, S. K. & Duffy, A. H. B. (2000). Evaluating a model of learning in design using protocol analysis, Sixth International Conference on Artificial Intelligence in Design – AID00. Worcester Polytechnic Institute, Worcester, USA.

[2] Sim, S. K. & Duffy, A. H. B. (1998). A foundation for machine learning in design, *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, Vol. 12, 193-209.

[3] Sim, S. K. and Duffy, A. H. B. (1998a). A Formalism for coupled design/learning activities, In Proc. Machine Learning in Design, Workshop (AID'98: Fifth International Conference of Artificial Intelligence in Design) ,18 July 1998, Portugal.

[4] Ericsson, K. A. and Simon, H. A., *Protocol Analysis, Verbal Reports as Data*, The MIT Press, 1993.

[5] Cross, N. and Cross, C. C. (1996). Design Protocol Data and Novel Design Decisions, in Cross, Christiaans & Dorst (eds), *Analysing Design Activity*, 35-63, John Wiley & Sons.

[6] Cross, N. Christiaans, H and Dorst K.(eds). (1996). *Analysing Design Activity* John Wiley & Sons, 1996.

[7] Grecu, D. L. & Brown, D. C. (1998). Dimensions of machine learning in design, *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, Vol. 12, 117-121, Cambridge University Press.