A NOVEL MODEL OF LEARNING IN DESIGN

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1   Introduction

Learning in design is a phenomenon that has been observed in design practice by many researchers. The observation that designers learn is supported by protocol studies in design that experienced designers can reach satisfactory design solutions more effectively than novice/naive designers. That there was no comprehensive model or theory of learning in design to explain the phenomenon was identified by Sim [1]. Hence a need was raised to develop a comprehensive model of learning in design that can describe the phenomenon and therefore serve as a basis to develop effective and efficient design support system(s) [1].

2   Criteria for evaluating models of learning in design

Sim [1] posited a set of criteria to evaluate existing models of learning in design to establish their capability of describing the phenomenon.

Explanative capability: Explanations are necessarily abstract statements that identify general properties, characteristics, and underlying processes and mechanisms for all possible instances of a phenomena [2]. They can be either based on evidence or based on a set of deductions derived from the tenets of the theory or models. Hence, a model or theory is said to have explanative capability if it is able to explain every observable instance of the phenomenon through its systems of abstract statements.

Predictability: For models or theories to exhibit predictability, they are characterised by a consistent set of statements and an inferential structure that can be used for prediction of events or conditions on the basis of assumed existing conditions [3].

Operationalisation: To construct effective explanations, all the terms and concepts used to form a theory must be operationalised [2]. These operationalisations must make it possible, in practice, to identify and classify, unambiguously, particular examples and states of the phenomena covered by the theory. Before operationalisation can occur, all terms and concepts must be subjected to an operational definition. An operational definition of a term is one which defines the term in connection to some physical or computational operation used to measure or quantify the defined entity.

Comprehensiveness: Miller [4] observes that the goal of science is the development of both special theories of limited scope, middle-range theories concerned with a greater number of phenomena and general theories that unify or integrate special and middle-range theories that

include a major segment of the total subject-matter of a field or of several fields. Hence, in evaluating the various theories/models that describe the cognitive behaviour of designers, a design theory will be considered as a special theory since it describes a single perspective of the cognitive behaviour of the designer; a theory of learning in design would be considered as a middle-range theory and that which describes the social cumulative cognitive process involving a team of designers would be considered as a general theory.

Applicability: The measure of applicability of a theory or model of design is the extent to which it has been applied to design of different artefacts or different types of design processes. It can be described as artefact independent or domain independent.

3   Review of models of learning in design

3.1   Existing models of learning in design

While there are numerous models or theories of design, only three models of learning in design have been identified. These are described below.

Exploration-based model: The exploration-based model of design [5] characterises design as an exploratory process in which there is a co-discovery of the nature of the design problem and its solution (see Figure 1). The co-discovery process explores the problem formulation in terms of a set of expected behaviours and the production of a set of technical specifications that will deliver the functionality described in the final requirement description (i.e. the design solution) through a collection of inter-related design activities. Underlying the exploration process is the knowledge change that occurs as the design solution evolves, the chronicles of which provides the knowledge of the design history.

The input knowledge is:

- *Initial design requirement* R_i: incomplete and inconsistent statement of the design requirement.

- *Design Knowledge Base* (DKB) which comprises of:
  Domain knowledge K_{dm}: knowledge of the possible design space to be explored.
  Design knowledge K_{dn}: procedural knowledge (e.g. design strategies, methods) about how the space can be explored.

The knowledge generated is the *Design Description Document* (DDD) that comprises of:

- *Final design requirement* R_f: a complete and consistent requirement description derived through the process of exploring the space of possible designs (SPD).

- *Final design specification*: a functional and structural description of the design solution.

- *Design exploration history* H_d: A record of knowledge acquired in the activities performed, the decisions made, and the rational behind each decision.

For the knowledge generated in DDD to be available for re-use during other design tasks, the DDD needs to be transferred to the DKB, built to support the class of problems concerned. The relationship between the DKB and the DDDs resulting from a series of design tasks is one of abstraction and generalisation and is an example of post-design knowledge change.
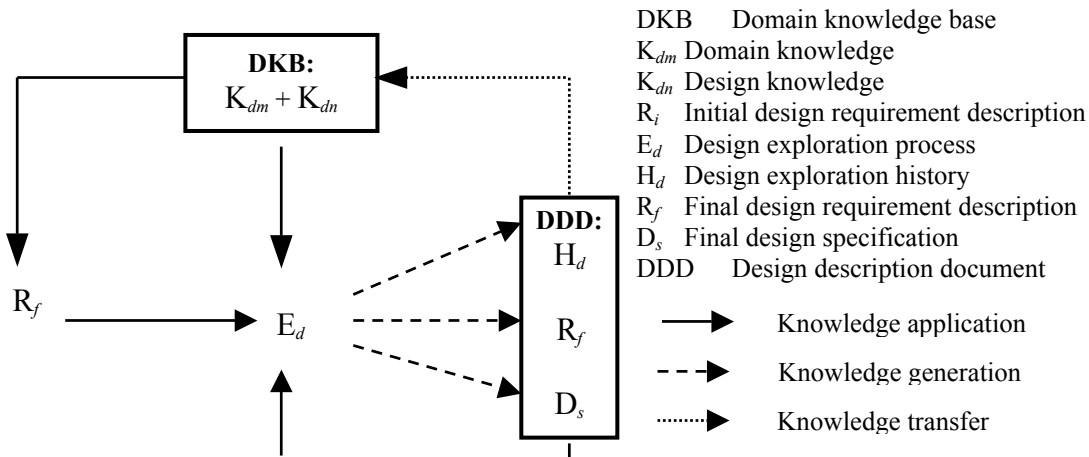
Figure 1. An exploration-based model of design [5]

Design Re-use Model: Duffy et al. [6] formulated the first engineering *Design Re-use Model* as illustrated in Figure 2. The knowledge components the processes are:

- *Design requirements*: refers to a statement of a design need/desire.

- *Domain knowledge*: knowledge pertaining to a particular domain.

- *Re-use library*: a storage location holding reusable (compiled) design knowledge, information and data.

- *Domain model*: represents a designer's conceptualisation of a design domain that is applicable to the current design problem.

- *Evolved design model*: a statement of an evolved design.

- *Completed design model*: a statement of a fully designed new artefact that is believed to satisfy the design requirements.

- *Design by Re-use*: the process in which knowledge resources are searched and useful knowledge can be identified, retrieved, and applied to the new design.

- *Domain Exploration*: the process of searching, understanding, generalising, and in general, "rationalising" the domain to gain an understanding of the features of that domain from which reusable fragments of knowledge can be identified, extracted, and stored for subsequent use in design.

- *Design for Re-use*: a process carried out to generate designs for subsequent re-use.

In this model, the knowledge learnt comprised of the completed design model, the domain model and the re-use library. Through the *Domain Exploration* process, the completed design model together with the domain knowledge is transformed into reusable fragments (chunks) of knowledge for subsequent use in design. Through the *Design for Re-use* process, knowledge generated in the evolved design model is acquired for subsequent re-use. In both these processes there is an increase in knowledge of the design. The design re-use model has been implemented in two systems, NODES [7] and PERSPECT [8] to demonstrate the learning of knowledge and subsequent application of that knowledge in design.
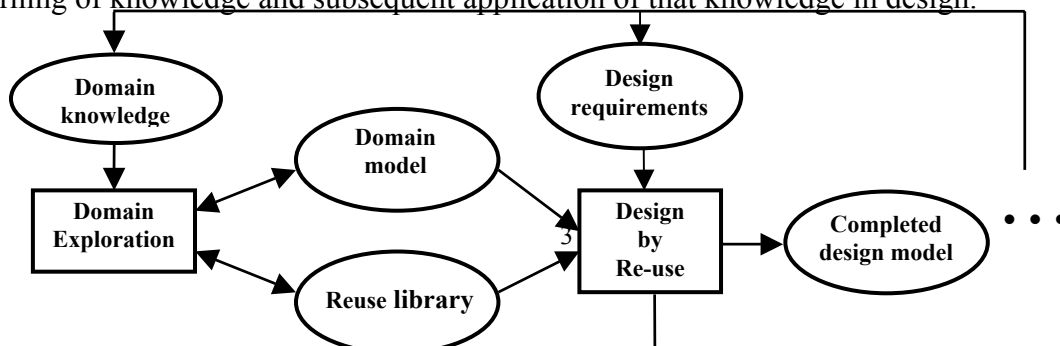
Figure 2: A design re-use model (Duffy et. al. [6])

The Design/Learning Loop: Duffy and Duffy [8] postulate how the activities of design and learning are coupled in Figure 3. The lower loop suggests in-situ learning and application of knowledge that occurs as the design solution is evolved from an initial stage, Stage: 1 to a design solution specification, Stage: N. In-situ learning occurs when knowledge learnt from the solution and its development is fed back to some store of experiential knowledge. Application of knowledge occurs when this knowledge is re-used to aid in the evolution to an acceptable design solution. Some of the learned knowledge will transform to long-term experiential knowledge to be re-used in later design scenarios whereas some of the transient knowledge learned will be used to assist in the evolution of the design. In addition to the lower loop, there is another loop that represents updates or modifications of the experiential knowledge depicting the designers' ability to explore and learn from their own knowledge.

Based on the Design/Learning Loop model, Duffy and Duffy offer a concept of computational learning that can ease the burden of knowledge elicitation and yet maintain (i.e. update and evolve) experiential knowledge depending on the knowledge needs of the designer. Hence, they introduce the concept of Shared Learning in which the designer and a computing system as a learning assistant co-learn when a designer learns new knowledge as a result of a learning assistant automatically learning and presenting previously implicit, and therefore unrepresented knowledge. Shared Learning is implemented in the system PERSPECT [8].

3.2   Evaluation of the models of learning in design

Explanative capability: The exploration-based model explains the design process as exploration of the space of possible designs in which an initial incomplete and inconsistent design requirement is modified into a final design specification. As a result of the exploration process, the knowledge gained in terms of what parts of the design space were explored, how and why decisions were made is recorded in the design history. The capturing of the design history, the final requirement description, and the associated design specification provides means by which knowledge can be learned retrospectively [1]. The design re-use model explains how knowledge that is generated during design can be stored for subsequent re-use. The recorded knowledge can be searched, abstracted into re-usable fragments and stored for subsequent use. It therefore explains an aspect of the phenomenon of learning in design in which knowledge is learned retrospectively.   In addition to learning knowledge retrospectively, the Design/Learning loop model is able to explain how design and learning can be coupled (i.e. in-situ learning during the design process).
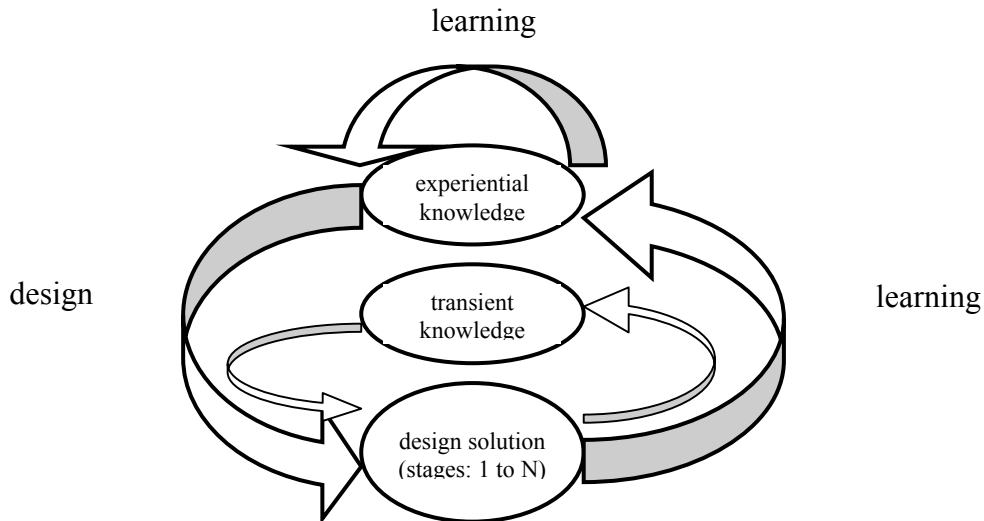
Figure 3: Design/Learning loop (Duffy & Duffy [8])

Prediction: Smithers et al. [9] observe that the exploration model lacks a formal description for it to be more predictive. The design re-use model does not feature any predictive capability in predicting when should learning take place or, given a design activity, what aspect of knowledge is relevant. The Design/Learning loop does not provide a formalism by which to predict different types of knowledge learned and how they are learned for different types of design activities. However, in the implementation of PERSPECT, the system is able to predict and therefore provide implicit knowledge available in explicit past design cases.

Operationalisation: Due to the nature of exploration, Smithers et al. [9] expect the operationalisation of the model to be domain dependent in terms of the exploration activities. But, in assessing the exploration model they determined that it lacks the use of knowledge in the control of the design process. Two systems, NODES and PERSPECT were implemented to show how the re-use model can be operationalised. The Design/Learning loop does not define a definite set of operators by which the users of the model can identify with for the implementation of the model. Nevertheless PERSPECT was implemented to illustrate some aspects of learning in design.

Comprehensiveness: Although the exploration model is meant to describe the design process, it has elements that support retrospective learning for design re-use through abstraction and generalisation of knowledge from similar DDDs. It therefore has a limited mechanism for learning. The re-use model is an example of a specialised model of learning in design as its architecture is aimed at learning abstract or implicit knowledge from past designs. The Design/Loop covers the phenomenon in terms of in-situ and retrospective learning. However, it is not a general model of learning in design as it does not explain how knowledge is learnt in the context of a typical repertoire of the design activities encountered in design practice.

Applicability: The model of design exploration was evaluated within the domains of preliminary design of water turbine [5]. Although the re-use model has been applied to preliminary design (e.g. NODES and PERSPECT), it is conceivable that it can be used in other design scenarios (e.g. design for manufacture, etc.) in which knowledge needs for different perspectives of the design cannot be harnessed directly from past designs. The Design/Leaning loop can be illustrated in the concept of Shared Learning in which the designer learns as the computational learning system learns [9].

3.3 Summary of evaluation

The evaluation of the three models is summarised in Table 1 below and suggests that:

- There was no general theory or model to describe the phenomenon of learning in design in a comprehensive manner.

- The existing models evaluated present some aspects of learning in design.

- For operationalisation to be successful, leading to the building of systems, there is a need for a clearly defined set of operators for design and learning.

Table 1: Evaluation of models of design and/or learning

Criteria	Models		
	Exploration-based	*Design re-use*	*Design/Learning loop*
Explanative capability	Some	Some	Some
Predictibility	Poor	Poor	Limited
Operationsa-lisation	A limited set of design operators	A limited set of design/learning operators	A limited set of design/learning operators
Comprehensive-ness	Retrospective learning	Retrospective learning	Retrospective/In-situ learning
Applicability	Few	Few	Few

To explain the phenomenon of learning in design more comprehensively, the model ought to feature the following characteristics:

- A formalism that represents the repertoire of typical design activities in which knowledge change that occurs can be explained in terms of the input knowledge, output knowledge and the goal of the design activity.

- A formalism that depicts the learning activity in terms of elements which explain what design knowledge is learnt, why learning occurs, how learning takes place, when is learning triggered and in what manner these elements interact [10].

- The nature of interactions that occurs between the design and learning activities (i.e. to postulate hypotheses on the nature of these links and substantiate them by evaluation).

4 LinD - A model of learning in design

Developing a model or theory of learning in design requires the knowledge of two human cognitive activities, that of design and learning and their interactions. The traditional research methodology in deriving a model or theory that is objective, universal and context independent is that of scientism. But the research methodology of scientism requires that results from two or more experiments under similarly controlled conditions to be the same. In the context of evaluating the model of learning in design, the dependence on human designers to be the subjects of experimentation in evaluating the model would pose a stumbling block in achieving unequivocally the same results in two nominally identical experiments. This is because no two designers are alike in their design practice. Hence, although the principal research methodology adopted here is that of scientism, the method of evaluation is not through experimentation as is the norm for traditional scientific method, but through the

protocol analysis of a case study of a designer at work [11]. Through the research methodology adopted, a model of learning in design called LinD has been developed.

LinD features formalisms for describing the cognitive activities of design and learning and three links that explain the interactions between these activities; epistemic, teleological and temporal link (see Figure 4). A mapping between a design activity and knowledge transformer ($A_d :: K_t$) shows the epistemic link between the design and learning activities.
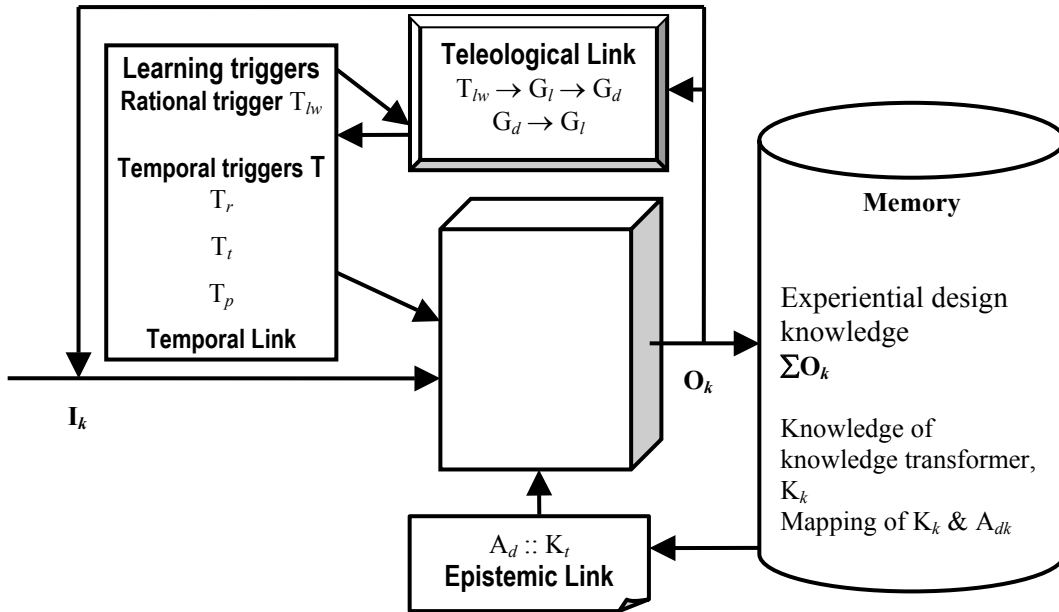

Figure 4 A model of learning in design, LinD [1]

Depending on the nature of the design activity, there are two possible ways by which design and learning goals interact that depict 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. $T_{lw} \to G_l \to G_d$). Secondly, the design goal precedes the learning goal (i.e. $G_d \to G_l$). 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 (learning) occurs in-situ or provisionally. But for certain types of experiential knowledge learning is of utility value if it is learnt in retrospect. Hence the model features three types of temporal learning triggers; retrospective (T_r), in-situ (T_i) and provisional (T_p)). For the retrospective learning trigger, the learning activity succeeds the design activity ($A_d \to K_t$). For the provisional learning trigger, the learning activity precedes the design activity ($K_t \to A_d$). For the in-situ learning trigger, the learning activity occurs concurrently with the design activity ($A_d \mid\mid K_t$).

The output knowledge, O_k, 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}.

6   Conclusion

Through the research methodology of pragmatic scientism, a novel model of learning in design called LinD was derived. The model has explanative capability in explaining the phenomenon of learning in design, although its predictive capability is limited [1]. Nevertheless, it is envisaged that LinD provides a formal basis upon which effective and efficient design system(s) can be developed.

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