ENVIRONMENT-BASED DESIGN (EBD): USING ONLY NECESSARY KNOWLEDGE FOR DESIGNER CREATIVITY

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ABSTRACT

Design is a highly nonlinear chaotic dynamic process with many possible solutions, which requires enormous knowledge for designers. This paper investigates how environment-based design (EBD) methodology can help designers use only necessary knowledge for their creativity based on three methods: information search, knowledge acquisition and knowledge application. The methods are applied in an aircraft pylon design, which is evaluated by two aerospace design specialists. The paper discussed the different roles of EBD for novice and expert designers in regard to overcoming emotion and knowledge barriers to achieving designer creativity.

Keywords: Conceptual design, Design methodology, Creativity, Environment-based design (EBD), knowledge

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1 INTRODUCTION

The goal of the design is to change the current environment ($\bigoplus E_0$) into a new environment ($\bigoplus E_1$) by designers, where the result can be creative. The design process follows a recursive nonlinear chaotic dynamic (Nguyen and Zeng, 2012; Yang et al., 2022; Zeng, 2001), with initial conditions determined by the designer's creativity capability, as shown in Figure 1.

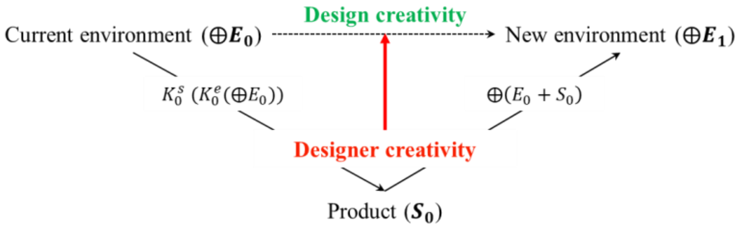

Figure 1. Designer creativity for design creativity (Yang et al., 2022)

Design creativity, mostly focused on the novelty and usefulness of a product, can be assessed by many ways (Sakar and Chakrabarti, 2011). Fiorineschi and Rotini conducted a systematic review of the methods to assess the novelty of a product (Fiorineschi and Rotini, 2021). Shah et al looked into how to access the ideation effectiveness with a focus on the idea generation process (Shah et al, 2003). In contrast, Hemmessey *et al* endeavoured to balance the following three factors: individual differences, the nature of creative products and the conditions that facilitate their creation (Hemmessey et al, 2011). In this paper, instead of considering if a product is creative in the context of the professional knowledge, we consider an individual's creative process by looking at how a designer designs a product that is in a field different from the designer's training.

The designer's creativity capability dictates how the design process can generate design solutions through the recursive formulation of the design states (Nguyen and Zeng, 2012; Yang et al., 2022). Different designers could produce distinctive design solutions for the same design problem, and even the same designer could produce distinctive design solutions at different times for the same design problem. Design can be seen as a knowledge-based problem-solving activity, in which knowledge is recursively linked to the problem and sub-problems (Chandrasekaran et al., 1992).

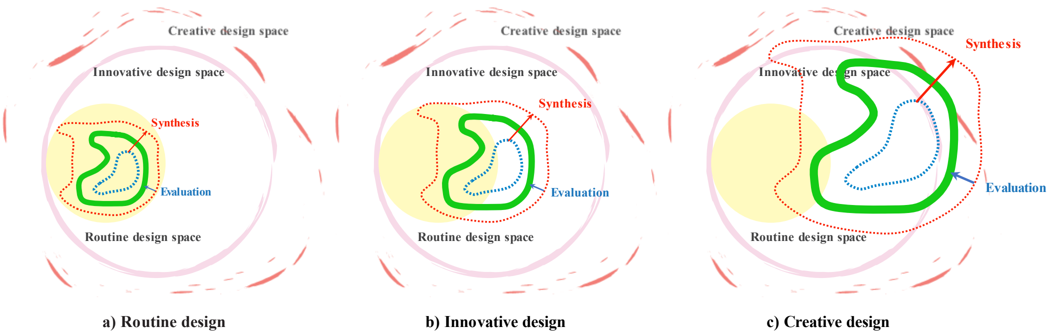

Figure 2. Design creativity: a) routine design – synthesis and evaluation operators act only on the routine design space; b) innovative design – synthesis and evaluation operators act on both the routine and innovative design spaces; c) creative design – synthesis and evaluation operators act on the routine, innovative, and creative design spaces. (Yang et al., 2022)

Design can range from routine to innovative to creative, with the boundaries of design spaces (Gero, 1990) determined by the knowledge and experience of the designer (Yang et al., 2022), as shown in Figure 2. According to Gero's classification (Gero, 1990), a design is routine if it proceeds within a design space of known and ordinary designs; it is innovative if it proceeds within a well-defined state space of potential designs but produces different designs; and it is creative if new variables and structures are introduced into the design space of potential designs. Proper knowledge use during the design process can lead to optimal mental effort and designer creativity (Yang et al., 2022). Design creativity relates to the designer's mental stress through an inverse U-shaped curve (Nguyen and Zeng, 2012; Yang et al., 2022). The mental capacity of designers, especially knowledge, skill, and affect,

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plays a vital role in knowledge use during the design process. Zeng et al. presented three ways for designers to use the knowledge for creativity: 1) formulating a design problem differently, 2) changing the strategy of environment decomposition, and 3) extending synthesis design knowledge) (Nguyen and Zeng, 2012; Yang et al., 2022).

Various design methodologies have been developed to assist designers creativity while processing knowledge. There are systematic design (Hubka and Eder, 1988), quality function deployment (QFD) (Akao, 1972), theory of inventive problem solving (TRIZ) (Altshuller, 1984), axiomatic design (Suh, 1990), structure, behaviour, function (SBF) model (Goel and Chandrasekaran, 1988; Goel et al., 2009), and the situated FBS model (Gero and Kannengiesser, 2004). The situated FBS model has been applied to different fields to help designers use their domain knowledge, such as technology forecasting (Dong and Sarkar, 2015) and social media (Emami et al., 2020) and individual user reaction (Becattini et al., 2020). Meanwhile, C-K theory modelled the design process by the extension and interaction between two interdependent spaces: concepts and knowledge (Hatchuel and Weil, 2003). Maier & Fadel (2009) proposed an affordance-based design to formulate a design problem regarding a designer–artifact–user (DAU) system. Environment-based design (EBD) is used to guide the design process when solving ill-defined design problems (Zeng, 2002, 2012, 2020).

EBD is a methodology that systematically guides novice designers and experts to search, acquire and apply knowledge. The core of EBD is that products come from the environment, serve the environment, and change the environment (Zeng, 2004, 2012). EBD has been effectively applied in various fields, including generating design requirements in medical device design (Chen et al., 2005), developing a manual of quality management systems in the industry (Sun et al., 2011), solving enterprise applications integrations problem (Tan et al., 2012), developing a model for design chain management (Liu and Zeng, 2009), and analysing human factors (Mohammadi et al., 2022; Wen et al., 2022; Yang et al., 2021). It has also been applied in education (Ma et al., 2022; Ommi and Zeng, 2018; Su et al., 2022), organizational management (Wang et al., 2017), and health domain.

This paper intends to explain how the EBD improves the effectiveness of knowledge use for designer creativity. The rest of the paper is organized as follows: Section 2 describes three processes in terms of information search, knowledge acquisition, and knowledge application. Section 3 shows a case study designing an aircraft pylon using EBD. Section 4 briefly discusses the case study results and the implications of the perspectives offered in the paper. Finally, Section 5 summarizes the paper.

2 METHODS

2.1 Information search

The information search aims to explore and find all the relevant information necessary and sufficient for designers to solve design problems. The initial design problem is typically ill-structured, making it challenging for designers to identify the required information effectively and efficiently from various sources. EBD methodology uses interactive question-asking strategies to guide the search process and save time and effort. Apart from traditional keyword searches, asking questions is an effective method for retrieving knowledge and collecting external information (Eris, 2004). Dorst & Cross (2001) also proposed a process to ask a quasi-standard set of questions in the design process. Recursive object models (ROM) (Zeng, 2008) are used to formulate the design statement and analyze the design problem effectively.

The information search process is divided into four iterative steps: 1) formulating design problems into a ROM diagram, 2) asking questions based on the problem ROM diagram, 3) answering questions based on an answering template, and 4) combining all answers into a merged ROM diagram. Recursive object model (ROM) is a tool representing a text in a graph that has three types of relations: constraint, connection, and predicate. The question-asking template (Wang and Zeng, 2009; Zeng, 2020) generates a list of questions based on keywords extracted from the ROM diagram. These questions help define the initial scope of design problems and workload, and predefined answer guidelines are used to catch supplied information as much as possible. Considering the recursive property of the design reasoning, the needed information keeps increasing and updating in the evolutions of the design problem, design knowledge, and design solutions (Zeng and Cheng, 1991). A stop rule is established to judge the adequacy of the information.

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2.2 Knowledge acquisition

Knowledge acquisition aims to acquire new knowledge from the information presented in the merged ROM diagram. This involves reasoning tasks (Chandrasekaran et al., 1992) where environment components are input, and conflicts are identified as output. A conflict arises when an object lacks the resources to perform its desired action in its environment or to accommodate the object's action in the environment (Zeng, 2015). Undesired conflicts between environment components can be identified using evaluation knowledge. In EBD, interactions are defined as a relation from one object to another that will generate a new object (Zeng and Gu, 1999) and are the focus for defining conflicts during knowledge acquisition. Interactions can be identified by analyzing the merged ROM diagram and expressed as facts usually indicated by verbs or gerunds in text. It is important to note that conflict differs from the notion of contradiction in TRIZ. Contradiction refers to propositions that assert incompatible or opposite things (Altshuller, 1984), whereas conflict refers to insufficient resources to trigger or support an object action.

2.3 Knowledge application

Knowledge application aims to use the appropriate knowledge to solve a problem involving three key steps. The first step is for designers to understand the problem by searching for information and acquiring new knowledge relevant to the problem. Designers identify the design tasks, including functions, constraints, and technologies, and identify explicit and implicit relationships between these requirements. This understanding is necessary to solve the problem properly.

The second step is to break down the problem into smaller sub-problems. EBD utilizes the environment-based decomposition strategy (Zeng, 2004, 2012; Zeng and Gu, 2001) based on environment components. The input of the decomposition is the defined design conflicts. As the new environment components are introduced to the current environment, new objects are created, or existing objects are refined.

The third step is to generate tentative solutions and decide on the final solution. Using the ROM diagram, all the necessary and sufficient information is embodied and organized within the product environment and processed to the required synthesis knowledge for designers to generate tentative design solutions. These solutions are evaluated through evaluation knowledge. The process is recursive until no conflict exists and the final design solution is determined.

3 CASE STUDY

The case study is to demonstrate how the EBD process can be used to design a product without prior domain knowledge about the product. A graduate student from Concordia University, with training in automation engineering and without any knowledge and experience in aerospace engineering, was assigned to conduct the conceptual design of a mechanical product - aerospace pylon. The initial statement of work is "configure mount system and pylon interface to install a PWC PW305A engine on a Bombardier CRJ700 aircraft rear mount".

A professor from Concordia University who is an expert in design theory and methodology taught the student how to use the EBD methodology in a medical device design project (Tan et al., 2011). The student completed the design within one month, working 20 hours per week on the project. An evaluation team, composed of researchers and aircraft design specialists from École Polytechnique de Montréal and École de Technologie Supérieure, was then invited to assess the student's design. The experts worked independently to evaluate the final conceptual design document. The details of the case study can be found in (Tan et al., 2013).

3.1 Information search

A ROM diagram is generated for the initial design statement, as shown in Figure 3. Based on the ROM diagram shown in Figure 3, the new understanding of the design problem is:

1. The design aims to configure the mount system and pylon interface.
2. The function of the mount system and pylon interface is to install a PWC PW305A engine.
3. The engine belongs to a rear mount of Bombardier CRJ700 aircraft.

Then, following the question-asking template in EBD, the questions are asked, and related answers are listed in Table 1. After answering the questions, more environment components and relations are identified. All answers are transformed into the ROM diagram to generate a merged ROM diagram.

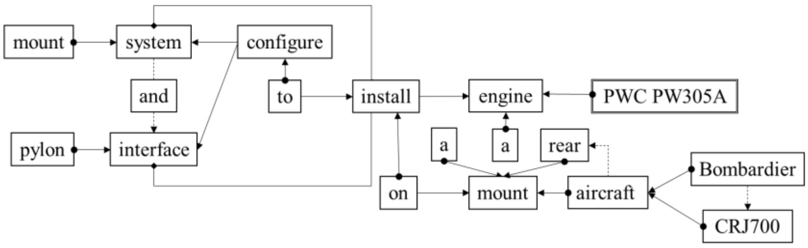

Figure 3. ROM diagram of the initial design statement

Table 1. Questions and answers derived from Figure 3

	Generic questions	Answers
Q1	What is a PWC PW305A engine?	A PWC PW305A engine is a turbofan engine for mid-class jets. (The load, operation status and included subsystems/features for this engine need to be clarified from a detailed engine specification/manual, namely, the OEM specifications).
Q2	What is a Bombardier CRJ 700 aircraft?	A Bombardier CRJ 700 is a Commercial Regional Jet aircraft produced by Bombardier.
Q3	What is an aircraft mount?	The mount is the interface used to connect the engine to the fuselage.
Q4	What is a mount system?	A mount system includes a frame structure to hold the engine to the pylon and a frame system attaching the pylon to the fuselage engine. In addition, it includes other systems that pass through the pylon and the interfaces that transfer control and sensory signals and resources.
Q5	What is a pylon?	The part of an aircraft's structure which connects an engine to either a wing or a fuselage through the mounting system (Spofford et al., 1994) (engine-to-fuselage in this case study). The major components may include but are not limited to forward engine mounts, aft engine mounts, skin, and inner structures (mid-spars) (Jonge, 1997; Spofford et al., 1994).
Q6	What is the pylon interface?	An interface allows internal mechanical systems (fuel, hydraulics and air systems) or/and electrical systems to pass through. (Martinou and Berjot, 2013; Moir and Seabridge, 2003). The lifecycle of the pylon interface includes manufacture, transportation, assembly, sales, maintenance, and disposal. The relevant environment components can be found in (Tan et al., 2013).
Q7	How to install it?	Connect the pylon to the fuselage mount and wire the necessary systems through pylon interfaces (OEM Specification).
Q8	Who to configure?	Designers/design team.
Q9	How to configure it?	Simple and light-weighted construction structure with very little or no aerodynamic penalty (Hackett and Schofield, 1992).

3.2 Knowledge acquisition

The novice designer identified the conflicts (not all) listed Table 2. More detailed processes can be found in (Tan et al., 2013).

3.3 Knowledge application

According to the rules defined by (Wang and Zeng, 2009; Zeng, 2015), conflicts resulting from the natural environment should be solved first; therefore, conflicts 1–5 should be addressed first.

For conflicts 1 and 4, it is important to consider the temperature profile from the front fan section of the jet engine, where the combustion chamber and the turbine section may rise to as high as 1500◦C and then cool down to 300◦C Figure 4. For the PW305A engine, the inter-turbine temperature limits are 785◦C for maximum take-off and continuous running but as high as 950◦C for about 2 seconds at starting transient (FAA, 2003)". As a result, materials that come into contact with the engine should be

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refractory, and the material's skin should be evaluated under thermal testing. For conflict 2, conceptual solutions include pipe sealing, fluid-dynamic analysis and fire detection & extinguishing system, anti-ice system, and bird collision testing. Conflict 3 can be addressed with low-temperature resistance material, anti-ice system, anti-corrosion coating and material, analysis & tests (electromagnetic test, bird collision test, stress & fatigue test). Conflict 5 can be solved by demanding an engine provider or building a protection device. Conflict 6 can potentially be resolved using standard operating procedures, error detection and warning systems, and automatic flying systems.

Table 2. Major conflicts identified from the merged ROM diagram

#	Conflicts	
1	The skin directly contacts the stratosphere (−56◦C)	The skin directly contacts a high-temperature area around (max. 950◦C)
2	Inflammable aviation fuel	The high-temperature area around (max. 950◦C)
3	The skin directly contacts the troposphere	Weather varies, atmosphere corrosion, and flying objects
4	Metal/alloy (perhaps) for all physical objects & Q/A	Material may present unwanted physical chemistry processes (crack, corrosion, becoming fragile, etc.) in certain conditions
5	Rotor burst	Material may present unwanted physical chemistry processes (crack, corrosion, becoming fragile, etc.) in certain conditions
6	Many human workers (designers, pilots, technicians, etc.)	Subject to human errors

Figure 4 presents the conceptual design sketches of the pylon with a forward mount configuration inspired by Boppe (1987), created by a novice designer. The action plan for pylon design was categorized into five levels, including project management, detail design, manufacturing, system integration, and service after launch, based on their work contents and required resources. These details are not included in this paper due to page limitations.

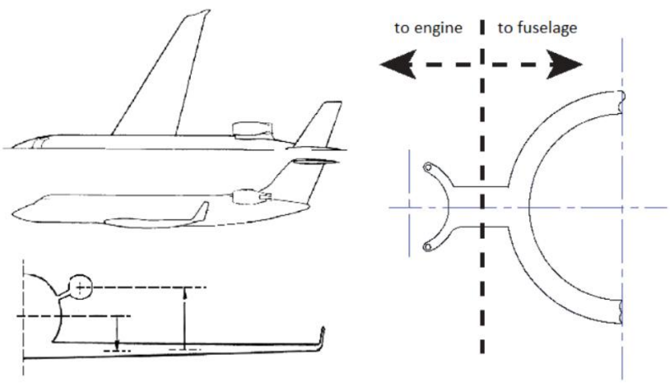

Figure 4. Conceptual design sketches of a forward mount configuration (inspired by (Boppe, 1987)) and the aircraft pylon

3.4 Expert evaluation of the student design and design process

A separate evaluation team evaluated the results presented in Figure 5 to determine the effectiveness and efficiency of using EBD to enhance designer creativity. Two senior experts evaluated the results using a set of criteria based on critical thinking concepts and tools (Paul et al., 2019). The evaluation results are summarized in Table 3, which shows that the designer's performance was outstanding in understanding the problem and its implications and consequences but limited in making inferences.

Overall, the evaluation indicates that the EBD procedure is effective in helping designers frame design problems and accurately identify conflicts. The ROM diagram also helps organize knowledge and present it in a structured and connected way for designers to generate design alternatives and evaluate

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their impacts. However, the limitation of the approach is that designers may lack relevant knowledge, particularly domain knowledge, which can result in a shortage of inferences.

Table 3. Results of evaluation from experts

Elements of thought	**Expert verdict**	**Expert comments**	**Examples**
Establishing purpose	N/A	The purpose is established by the existence of a statement of work	N/A
Understanding the problem	Outstanding	The conflict identification step of the EBD methodology produced surprisingly accurate results. Some of these conflicts are only recognized by novice designers late in the design process.	Critical temperature envelopes at different stages of a given flight path
Identification of assumptions	Good	Most assumptions were well justified in the case study, and their criticality was well established.	Material failure due to the manufacturing process
Specification of viewpoint	Good	The various stakeholders are well established, and their roles are understood in the design process	Certification bodies and role of standards. Process understanding
Data, information and evidence	Average	One of the great challenges and particularities of aircraft design is the overload of information at the engineer's disposal. Some data is indeed available to the general public, but IP concerning testing and aerodynamic profiling, for example, prevents most of the wealth of data from being visible to non-professionals.	Aerodynamics and testing data
Concepts and theories	Good	The concepts and theories behind aircraft design are well established, and the body of knowledge is widely accessible. These were nonetheless correctly reutilized	Use of computer tools to perform specific simulations
Inferences	Limited	In such complex systems, the design choices' interpretation is a very difficult analysis, even for experts. Here some interpretations showed a lack of knowledge concerning the business aspects governing the work statement.	Rotor burst prevention and partner responsibility
Implications and consequences	Outstanding	The ROM diagram was a view that experts could use to focus on strategic impact analysis of design choices	Overall ROM diagram

4 DISCUSSION

4.1 How can the EBD help expert creativity?

Experts designers have rich domain-specific knowledge, experiential knowledge and goal-limited strategies (Popovic, 2004). Experts use previous design strategies (Ahmed et al., 2003) and experience to help them generate solution conjectures (Cross, 2011; Lloyd and Scott, 1995). Improper knowledge leads to design fixation inhabiting the designer creativity (Yang et al., 2022). Fixation occurs when designers fail to appropriately transfer knowledge from experience or prior situations (Nguyen and

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Zeng, 2017). Experts' perceptions can be manipulated by their prior knowledge to some extent and mismatch the perceived fitness. Design fixation will block the ability to perceive the problems, represent environment components and generate alternative solutions. At the knowledge application step in EBD, the environment-based decomposition strategy happens when no product or function exists. This situation can prevent designers from using their previous experience to solve problems.

4.2 How can the EBD help novice's creativity?

Novices designers have limited experiences and explicit and tacit domain knowledge. Novice designers use trial and error to tackle design tasks (Ahmed et al., 2003). Novices could have knowledge barriers as a lack of knowledge and experience, and logic barriers as thinking strategies (Yang et al., 2021).
Proper designer knowledge maintains the designer's mental stress to the right level to trigger creativity (Yang et al., 2022). Different knowledge can be used to formulate a design problem differently (Nguyen and Zeng, 2012; Yang et al., 2022). Information search and knowledge acquisition steps can extend new and different design knowledge for expert designers step-by-step. The interactive question-asking information search strategy helps designers, especially novices, to collect all the relevant information in the product environment. Novice designers always do not know what to ask or fail to ask the right questions (Ahmed et al., 2003; Wallace and Ahmed, 2003). The information-gathering strategy in this paper is hybrid, rather than depth-first and breadth-first, which is considered an excellent way to minimize uncertainty in the problem formulation process (Wang et al., 2015). With the ROM diagram application, the intention of design problems can be identified and represented based on semantics. Compared with keyword search, the question-asking method effectively expands the design boundary because the required information is more precise and concrete. The designers of the aircraft pylon's conceptual design are novice designers with no aerospace engineering expertise within a limited time. All the information used in this design process was obtained online using EBD, and no extra assistance was acquired during the research. Since the entire process is guided by EBD, it proves that this design methodology can help novice designers search for and apply necessary knowledge in an effective and efficient manner.

5 CONCLUSION

Herein, this paper presents the EBD design methodology to uncover the roles of knowledge in designer creativity, based on which three methods are recommended to use the knowledge in design. Information search is for "what information do you need to search," knowledge acquisition for "how to extract knowledge", and knowledge application for "how to apply knowledge." It provides a procedure to use only necessary knowledge for designer creativity. It is advantageous for novice designers to quickly adapt to a new field and guide them on where to start with.

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