A STUDY OF THE EARLY-STAGE ENGINEERING DESIGN ACTIVITIES IN PRACTICE

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ABSTRACT

The early-stage engineering design activities include conceptualising, identifying, and solving an engineering design problem. These activities are essential and standard roles of a design engineer. However, they seem to lack comprehensive practice within the engineering design community. In this study, semi-structured interviews conducted with 18 participants having engineering design backgrounds are presented. The aim of the interviews is to investigate the awareness and practice of the early stage engineering design activities. The participants interviewed practice in countries including France, the United Kingdom, and the United States. Contrary to standard expectations, the results of the interviews show that the early-stage engineering design activities are not comprehensively practised. The results suggest that design engineers' crucial role in identifying unknown problems lacks practice. Also, the data from the interviews provide empirical evidence on the determinants for the lack of comprehensive practice of early-stage engineering design activities. Recommendations on possible interventions to support the practice are presented to expedite innovations and inventions.

Keywords: Design engineering, Early design phases, Design practice, Problem-solving, Problem-exploring

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1 INTRODUCTION

Engineering design is a field envisioned to produce creative design engineers as "innovators of future technologies" (Jorgensen et al., 2011). Innovators are expected to "identify a societal problem and come up with a preliminary idea (or ideas) for a potential solution" (Molecke and Pache, 2019). These activities describe the Early-Stage Engineering Design (ESED) - characterised by "idea-generation" activities (Belanger et al., 2022). Although the ESED activities are related and complementary, they can be grouped into two distinct aspects. One is coming up with an Engineering Design problem (EDP) through conceptualization or identification (Olewnik et al., 2020). The other is coming up with an Engineering Design Solution (EDS) or solving an EDP (Vale et al., 2020). These aspects of practice are recognised as a design engineer's standard roles (NAE, 2004). Usually, problems solved in engineering design come from market-pull (problem-oriented) or technology-push (solution-oriented). Market-pull EDP comes from an apparent market need, while Technology-push EDP is one identified to be solved with a breakthrough solution. Market-pull EDP is incremental or takes time to be self-evident, and technology-push EDP is "radical" or not initially based on a market need (Brem and Voigt, 2009). However, market-pull and technology-push EDPs emerge as reactive measures to a self-evident problem or breakthrough solution, respectively (Dixon, 2001). Apart from market-pull and technology-push, there is often a neglected proactive process through which a new EDP could emerge. This process is called Engineering Design Problem-Exploring (EDPE) in this study. It relates to Fuzzy Front End, whereby ideas and unknown concepts are generated to keep innovating a specific product (Gassmann and Schweitzer, 2014). However, EDPE is a conscious effort to conceptualise, create, and identify an EDP independent of any self-evident problem, breakthrough solution, or specific product innovation. A "created" EDP would not exist until a design engineer conceptualises it to make it an apparent EDP. It does not have a known formulation, method of solution, or solution (Getzels, 1979). A created EDP leads to inventions (Kirjavainen and Björklund, 2019) and drives technology-push. Within the engineering design community, the comprehensive practice of ESED activities seems to be lacking. The focus appears to be on Engineering Design Problem-Solving (EDPS) or developing an EDS while EDPE is neglected. This neglect is worrisome and suggests that there may be a lack of understanding of the 1) comprehensive ESED activities, 2) importance of EDPE and EDPS as complementary aspects in engineering design, and 3) consequences of not practising the ESED aspects comprehensively - a critical oversight. Although relatively few studies highlight the lack of attention on EDPE (Obieke et al., 2020; Ding et al., 2019; Getzels, 1979), empirical validation and investigation of determinants lack.

The aim of this study is to investigate the understanding, awareness, and practice of ESED activities in engineering design. Interviews with 18 participants with engineering design-related backgrounds provide empirical evidence corroborating previous information on the lack of attention on EDPE. It also reveals possible determinants of the lack of EDPE practice and the challenge in the process. The determinants suggest that interventions are required, including support tools, academic support, and industry support, which are lacking. Particularly, observational evidence on the relative difficulties involved in EDPE and EDPS suggests EDPE requires computational support, amongst others. Such support aligns with the vision of the fourth industrial revolution to leverage computational technologies to support challenging tasks (Horváth and Szabó, 2019). Albeit a challenging activity, no specific support tool is available for EDPE that has been widely adopted, unlike EDPS, and research in this direction is lacking. Encouraging EDPE would deliver increased societal/economic benefits while enabling design engineers' skills. Furthermore, EDPE and EDPS are complementary for innovations and inventions of societal and economic benefits.

Presented in the following section is a literature review of the ESED activities and the research question addressed in this study. In Section 3, the interviews conducted with industry professionals are presented. The results of the study are presented in Section 4. In Section 5, the results of the study are discussed. The conclusions and future work of the study are presented in Section 6.

2 EARLY-STAGE ENGINEERING DESIGN (ESED) ACTIVITIES

EDPE and EDPS are ESED activities where conceptualisation is essential to develop an EDP and EDS. A new EDP or EDS could be conceptualised or identified independently of each other, and the processes require creativity. According to Amabile (1983), creativity is best imagined as a "behavior resulting from particular constellations of personal characteristics, cognitive abilities, and social

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environments." As a "behavior", it implies that creativity can be developed. Macnab (2011) defines creativity as the "act of making or inventing an entity that didn't exist before." Recently, creativity has been defined as the "forming of associative elements into new combinations which either meet requirements or are in some way useful" (Childs et al., 2022). Albeit EDPE and EDPS are complementary, as shown in Figure 1, they could be independently practised for increased innovation and invention (Litzinger et al., 2010). According to NIPO (2022), an "invention must represent a practical solution to a problem". Hence, addressing an EDP is a determining factor in considering an inventive solution (Borgianni et al., 2021). Also, the usefulness of an EDS depends on the EDP it addresses and how it compares with existing solutions. However, the effort in supporting both EDPE and EDPS in engineering design education, research, and the industry lacks where the focus is on EDPS. At the same time, the equally important EDPE is ignored. For example, Han et al. (2021) explored whether individual or group work is more beneficial for fostering students in generating creative solutions; Karwowski et al. (2020) investigated the relationship between creativity and learning by testing how participants produce creative solutions through combining, modifying, or transforming ideas; Crilly (2019) explored the effect of fixation on design creativity, particularly problem-solving, among students and professional designers in industry; a study by Tekmen-Araci and Mann (2019) suggests that some instructors in engineering design education understand creativity to apply just to problem-solving, and they transfer the same knowledge to students. These examples show that EDPS is usually the focus of several engineering design and creativity discussions in academia and industry. Although EDPS is important in engineering design, the significantly relative lack of attention on the equally important EDPE aspect should be a concern, as Obieke et al. (2023) highlighted. Unlike EDPS, there are relatively few studies on EDPE.

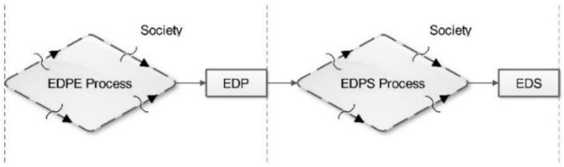

Figure 1. Early-stage engineering design activities and outcomes

In Figure 1, the activities performed at the early-stage of engineering design are shown. These activities are performed with the consideration of their societal values, as indicated in Figure 1. They are expected roles of a design engineer, as could be inferred from the statement: "If an engineer's reason for being is to identify societal problems, and then to find (somehow optimized) solutions for those problems, then it stands to reason that compassion could be an important engineering value" (Vale et al., 2020). This statement is based on a research result indicating a low rating for 'compassion' as a factor that affects engineering design decisions. The Research Question (RQ) addressed in this study is "*Do design engineers understand and practice EDPE?*"
The processes shown in Figure 1 require creativity to produce two distinct results, EDP and EDS. They involve divergent and convergent thinking (Aranda et al., 2019). The continuous focus on EDPS only and creativity as an EDPS phenomenon has increasing consequences, including making the EDPE creative ability of a design engineer dormant. As a consequence, this could impact inventions and innovations in engineering. An unknown EDP would delay a novel EDS. "Instead of reacting to unexpected problems" or existing EDPs only, there is a need for design engineers to constantly engage in "finding new opportunities," challenges, or EDPs (Sawyer, 2013). Albeit "it is difficult to identify a design problem for which no benchmark solutions exist" (Kershaw et al., 2019), it is not impossible. The difficulty in EDPE may be due to limitations in natural ability. However, there is a need for empirical data on this, and computational augmentation could be helpful.

3 METHODS

Qualitative methodology is used mainly in this study. It is a desirable approach to profound insights into a topic in a field by interacting with people in that field (Clark et al., 2021). Hence, it is used to understand the awareness and practice of ESED activities in engineering design and the associated challenges. Semi-structured interviews (Brinkmann and Kvale, 2018) are conducted with 18 participants within the engineering design community. This interview style allows for a more in-depth

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understanding and interpretation of participants' responses. During the discussion, there is a careful observation "not to influence the respondent to answer questions a certain way" (Gall et al., 1996). The participants freely provided uninfluenced responses based on their experience and knowledge. Each interview session lasted between 30 - 60 minutes, and participants provided consent to record the sessions for the research and permission to use their data for publications. The interview began with introductions and an explanation of the purpose of the discussion. The details of the interview discussion themes are presented in Table 2. Using NVivo software, the interview responses are transcribed verbatim and qualitatively analysed, including a Word Frequency Analysis (WFA). The participants' response data are queried for connections and visualised using a word tree - a graphical display of word connections (Wattenberg and Viégas, 2008). The WFA produced quantitative data analysed/visualised using python libraries - Seaborn and Matplotlib. Observations are used during the interviews to validate some of the participants' responses.

Participants

Table 1. Interview participants' detail

Number of Participants = 18						
Job Title (Participants' Number)	Experience [in years]	Qualification			Creativity (Participants' Number)	
		BS	MS	PhD	Creative	Taught
Design Engineer (12)	1 - 7	6	5	1*	Yes (12); No (0)	Yes (5); No (7)
Industrial Designer (4)	3 - 7	2	2	0	Yes (4); No (0)	Yes (0); No (4)
Mechanical Designer (1)	3	0	1	0	Yes (1); No (0)	Yes (1); No (0)
Project Design Manager (1)	7	0	1	0	Yes (1); No (0)	Yes (0); No (1)

*BS - Bachelors, MS - Masters, *Currently studying for the qualification*

Information about the 18 participants in this study is shown in Table 1. In many studies, 18 participants are used (for example, Fu et al., 2019; Strömberg et al., 2018). This study's participants all have engineering design/design-related backgrounds in various countries, including, in alphabetical order, Canada, France, India, Russia, the United Kingdom, and the United States. In Table 1, the overall mean, standard deviation, and range of the work experience of the participants are 4.6, 2, and 6, respectively. As indicated in the table, the participants are asked whether they consider themselves creative and are taught creativity at the University or at work. The response is used to understand the focus on academic creativity, as discussed in Section 5. A participant's response on whether they were taught creativity is "I do not know". This response is classified as a "No" in Table 1. One of the reasons for this classification is uniformity, and another is that creativity is a phenomenon that should be remembered in engineering if taught. Researchers "believe that ‘creativity’ should be taught in schools as a method of science, thus allowing students to recognise that science is an activity that involves creativity" (Hong et al., 2022).

Interview themes for data collection and analyses

Table 2. Discussion themes during the interview

	Discussion Themes
1	How would you describe your core responsibilities or roles as a design engineer?
2	What can creativity help designers to achieve?
3	Do you consider yourself creative?
4	How do clients present/communicate their design problems to you?
5	How do you think the problems we solve in engineering design come about?
6	Have you ever consciously tried to come up with a new problem?
7	How would you describe the thinking process of identifying a new problem that is unfamiliar or does not previously exist?
8	Could you think of a new problem in one minute?
9	Does your personal background/experience/knowledge play a role in your inspiration through combining different solutions?
10	When you see a need [like this] without additional information, does it prompt you to think of possible solutions based on your experience, background, and knowledge?
11	Would you consider identifying the problem more important or finding the solution?

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The participants provide oral responses to the themes in Table 2. In Theme 1 of the interview discussions, the participants are asked the question relative to their job title, as stated in Table 1. For example, the participants are asked to describe their roles as industrial design engineers, design engineers, or mechanical design engineers. Careful observations are made during responses, particularly to some of the questions. In this study, the observations in Themes 8 and 10 are used as triangulation (Gall et al., 1996), to check the validity of responses in Themes 7 and 9. The credibility of a participant's response to Themes 7 and 9 is further interpreted with the observational evidence from their response to Themes 8 and 10, respectively. It should be noted that, albeit sequential, the order of the themes in Table 2 is not in immediate succession. There are discussions between the themes not presented in this study. Similar to triangulation, some responses from the participants are complementarily interpreted to provide complete information.

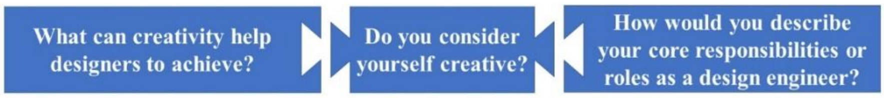

Figure 2. Complementary questions for EDPE and EDPS practices

As shown in Figure 2, Themes 1 - 3 in Table 2 are complementarily interpreted. This is for a profound understanding of the participants' awareness of the EDPE and EDPS aspects illustrated in Figure 1. Theme 1 directly tests the participants' awareness of EDPE and EDPS aspects. Since creativity is important in both EDPE and EDPS, Theme 2 tests the participants' general understanding of creativity's applicability in engineering design. In addition, the personal creativity understanding of the participant is tested with Theme 3. A follow-on discussion on Theme 3 is for the participants to provide further details on why they are creative or uncreative. These three complementary themes should prompt an automatic recall of EDPE and EDPS aspects if the participants have an active/dormant knowledge of them. Similarly, Themes 4, 5, and 6 are complementary. Observations and responses in Theme 5 are used as triangulation for Themes 4 and 6, as discussed in Section 5.

4 RESULTS

Participants' awareness of EDPE and EDPS

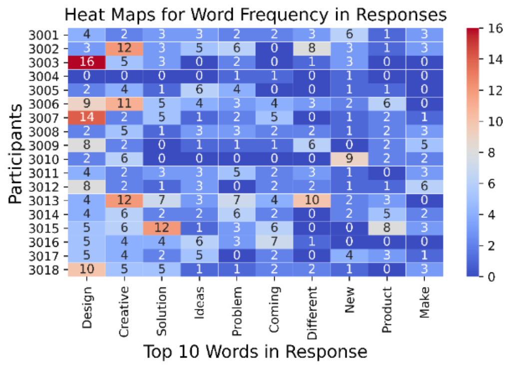

Figure 3. Top 10 frequent words in participants' responses

Responses to Themes 1 - 3 in Table 2 are *coded* - selecting descriptive lines of words in NVivo, and WFA is performed. The top 10 frequent words in the participants' responses are shown in Figure 3, with the participants' names classified to protect their identities. In studies, using the top 10 frequent words for analysis is typical (for example, Homan et al., 2022). The top 10 words are obtained by removing *stop words* or words with unrelated meanings to the analysis (examples include "just" and "like"). The minimum length of the frequent word queried is three because words less than three characters would not be meaningful for analysis. Words that are similar in meaning are stemmed. For instance, "creative", "creatively", and "creativity" are stemmed from one word - "creative". As shown in Figure 3, the participants focused on different areas in responding to the complementary themes. It could be seen that Participant 3003 used the word "design" 16 times in explaining their roles or the application of creativity in engineering, while Participant 3015 used the word "solution" 12 times. A text search is performed for the numbers, especially the higher ones, indicated in the heat maps. Participant 3003, for example,

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mentions that "creativity, to me means *design* freedom" in Theme 2, and "to develop and *design* a model and then extract a drawing from this model" in Theme 1. Overall, "solution" is used 56 times for all participants and "problem" 54 times. As the intent is to observe the awareness of design engineers about EDPE and EDPS, the interest is on the contextual usage of the top 10 frequent words "problem" and "solution. Hence, the participants' responses are further queried to obtain the word tree results in Figures 4 and 5. The results provide the first evidence of the participants' awareness of EDPE and EDPS.

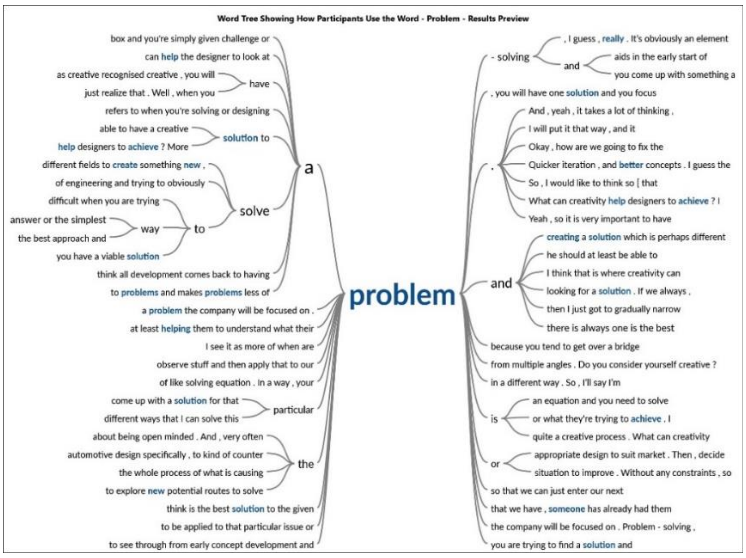

Figure 4. Participants' contextual usage of the word "problem" in theme response

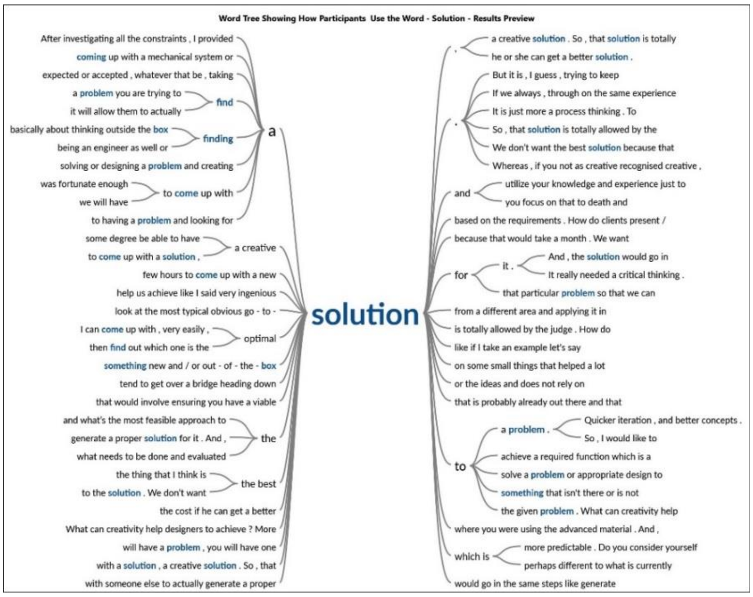

Figure 5. Participants' contextual usage of the word "solution" in theme response

In Figure 4, all the root word "solution" occurrences in the participants' responses are displayed in a line of 17 words (8 on either side of the root word) to understand its contextual usage. Similarly, in Figure 5, the contextual use of the root word "problem" is shown. The two figures give insights into how the usage of the two terms relates to EDPE and EDPS. In addition to the information in Figures 4 and 5, some direct questions about EDPS and EDPE provide more supporting evidence during the interview. These questions are included in Table 3, alongside the responses from the participants. In Theme 10, either one of two EDPs/briefs is presented to the participants. EDP1 - "Design a device to improve mobility for low-income persons with physical disabilities" - is previously used in a study (Koronis et al., 2021). EDP2 - "Design of an automatic self folding dining table"- is artificially generated (Obieke et al., 2021). The empirical evidence about EDPE practice presented in this section, and discussed next, is not hitherto available in the literature. Hence, this highlights the novelty of this study.

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Table 3. Interview Themes 4, 5, 6, 7, 8, 9, 10, and 11 and response interpretations

Themes and Response Interpretations	
Theme 4	How do clients present or communicate their design problems to you?
Response	Modes include verbal and written communication and visual aids (images or physical items). However, most of the participants receive EDPs from clients in textual form.
Theme 5	How do you think the problems we solve in engineering design come about?
Response	Two participants mentioned, "I would say culture and observation" and "for example, people in the olden days they were struggling a lot". The rest of the responses are based on either market competition or clients wanting to improve their products.
Theme 6	Have you ever consciously tried to come up with a new problem?
Response	The responses indicate that the participants rarely engage in this thought process consciously. Although nine participants said "Yes" on this theme, five said "No", and four were "Unsure". Two participants that said "Yes" revealed that the thought was due to a problem they were solving. The rest did so by chance. Two participants also mention that they often align more with seeing or detecting a problem that may not be obvious.
Theme 7	How would you describe the thinking process of identifying a new problem that is unfamiliar or does not previously exist?
Response	Most participants agree that coming up with a new EDP is challenging.
Theme 8	Could you think of a new problem in one minute?
Response	Ten participants said "No", and eight said "Yes". However, when put on the spot, only three out of the eight that said "Yes" mentioned a problem, while five reverted to saying that what they already know prevents them from thinking of anything else.
Theme 9	Does your personal background/experience/knowledge play a role in your inspiration through combining different solutions?
Response	100% strong "Yes" answer.
Theme 10	When you see a need [like this] without additional information, does it prompt you to think of possible solutions based on your experience, background, and knowledge?
Response	The responses from the participants are all in the affirmative. The participants spontaneously progressed to providing possible solutions to the brief/EDP presented.
Theme 11	Would you consider identifying the problem more important or finding the solution?
Response	61.11% (11 participants) - identifying a problem; 33.33% (6 participants) - both; and 5.56% (1 participant) - identifying a solution. The participants brainstormed to respond.

5 DISCUSSIONS

Distinct ESED activities

The results of this study provide evidence of the distinct, albeit complementary, aspects of engineering design. Responses to Theme 4 of the interviews confirm that participants receive EDPs from clients mostly in text, albeit ill-defined. The responses further confirm that EDPE could be performed independently of EDPS. The EDPs are independently conceptualised, discovered, or identified by the clients before consulting the design engineers for an EDS. Unfortunately, EDPE is an expected role of design engineers, which has received scarce attention over the years. The education, knowledge, and skills of design engineers are an added advantage for EDPE.

Addressing the research question

The RQ in this study, as presented in Section 2, is "*Do design engineers understand and practice EDPE?*" Themes 1 - 3 of the interviews are complementarily designed to prompt the participants to recall EDPE and EDPS aspects. The heat maps in Figure 3 show the top 10 frequent words in the participants' responses to Themes 1 - 3. In Figure 3, the top 10 words - "problems" and "solution" are used 54 and 56 times, respectively. However, as shown in Figures 4 and 5, the participants' contextual usage of "problem" and "solution" are relative to EDS and EDPS. No explicit context associates the top 10 words with EDPE or identifying an EDP. Hence, this shows that the participants describe their roles and understanding of creativity relative to EDPS without explicitly referencing EDPE. As presented in Table 1, some participants are not taught creativity in academia or industry, although they consider themselves creative. It could be inferred that the participants' understanding of creativity stems from information provided in academia (for those taught creativity) or literature. The understanding of

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creativity as only an EDPS phenomenon propagates to experts and experienced design engineers. In a study by Ahmed (2007), "26 interviews were carried out with senior level design engineers", including chief engineers. The participants in Ahmed's study believe creativity skills contribute to becoming an expert in engineering design. Their views in that study are sustained relative to EDPS. Much of the literature in engineering design discusses creativity from the EDPS perspective only, as presented in Section 2. There is a need to review the creativity teaching in engineering design education mainly to reflect its importance in EDPE. The analyses of the participants' responses to Themes 1 - 3 show that they do not have EDPE as an active knowledge and answer the RQ. The association of creativity with EDPS only contributes to the neglect of EDPE in addition to those discussed next.

Relative difficulties in EDPE and EDPS

Considerable observational evidence in this study supports the literature's indications that identifying an EDP is more challenging than coming up with an EDS (Grigorenko, 2019). When the participants are shown an EDP/brief in Theme 10 Table 3, they almost effortlessly respond with suggestions of possible EDS within seconds. However, the responses in Theme 8 Table 3 show that, relative to an EDS, the participants struggle to think of an EDP more. After an attempt to brainstorm, ten participants said "No" in Theme 8 Table 3. Eight participants initially said "Yes" in Theme 8 Table 3 and were asked to think of a new EDP. After an attempt, five of the eight participants could not come up with an EDP and mentioned that what they already know prevents them from doing so. Only three of the eight participants came up with an EDP. However, two of the three participants that came up with an EDP mentioned they had already thought of the EDP previously, and it is not an on-the-spot outcome. Responses in Themes 6, 7, and 8 indicate that EDPE is scarcely practised in engineering design. Observational evidence in Theme 8 provides credence to the responses in Theme 7. Similarly, observational evidence in Themes 8 and 10 enables a comparison of the relative difficulties in the practices of EDPE and EDPS. Comparatively, observations from the interviews show that EDPE is more challenging than EDPS practice. However, more practice and support could reduce the challenge. A difficult task could lead to abandonment (Martin, 2015). A computational support tool, which lacks, could be helpful in the EDPE process, as discussed next. Two participants mentioned in Theme 6 Table 3 that their mind aligns more with detecting conceivably unobvious EDPs outside any EDPS process, which suggests that EDPE is an ability that can be encouraged just like EDPS.

Sources of EDP and Computational support for EDPE

As mentioned in Section 1, EDP could come from market-pull or technology-push. As presented in Section 3, Themes 4, 5, and 6 are complementary, and Theme 5 is used as triangulation for Themes 4 and 6. The observations and responses in Theme 5 show that the participants react to EDPs from clients. The sources of EDP they mention are mainly based on innovation or improving on obvious problems observed or presented by clients. However, some responses guide how a new EDP could emerge from other sources. For example, in Theme 5, a participant mentions that an EDP could arise from "culture and observation". This response implies that a design engineer could come up with a new EDP based on an observation that coincides with their knowledge, experience, or background as they could in EDPS (based on responses to Theme 9). "Some of the most powerful projects come from personal experiences, particularly when those experiences clash with the dominant wisdom" (Dennis and Valacich, 2001). Also, a participant mentions in Theme 6, "I guess sometimes I think a lot of people must just think what's the next?" Indeed, it is possible to think this way and create an EDP out of nothing. For example, "I sometimes begin drawing with no preconceived problem to solve, with only a desire to use pencil on paper and only to make lines, tones and styles with no conscious aim. But as my mind takes in what is so produced a point arrives where some idea becomes conscious and crystallizes, and then control and ordering begin to take place" (Moore, 1995). As earlier mentioned, "it is difficult to identify a design problem for which no benchmark solutions exist" (Kershaw et al., 2019). Themes 6, 7, and 8 results suggest that coming up with a new EDP is challenging. However, design engineers could recognise an EDP without a solution based on their experiences, knowledge, and cultural backgrounds. Hence, it would be supportive if a computational approach could be used to come up with a new EDP while design engineers apply their knowledge, experiences, and backgrounds to define the EDP. It is noted that the "design process is shaped in fundamental ways by the fact that human rationality is bounded, and shaped especially by the very narrow focus of human attention. Computers enable us to handle a little more information than we could before" (Simon, 1995).

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6 CONCLUSIONS AND FUTURE WORK

The ESED activities practised by design engineers are investigated in this study. These activities are important in engineering design and include conceptualising, identifying, and solving an engineering design problem. Few studies highlight these activities' lack of comprehensive practice without empirical evidence. Semi-structured interviews are conducted in this study with 18 professionals in countries including France and the United Kingdom. The interview results show that EDPE, or conceptualising and identifying new EDPs, are scarcely practised at ESED. This seems to be a critical oversight as new EDPs drive technology-push, inventions, and innovations. The results also reveal the relative challenges associated with ESED activities. Data and observational evidence from the interviews suggest that, as ESED activities, EDPE is more challenging to practice than EDPS. This seems to be a determinant of the lack of EDPE practice. Another determinant appears to be the non-consideration of EDPE in academia, especially in teaching creativity which is vital for EDPE. Over the years, EDPE skills and tools have lacked academic support and research. This study contributes by highlighting, with empirical evidence, an important but neglected aspect of engineering design. Further, it suggests academic and computational interventions to support EDPE practice. In future work for this study, computational support intervention for EDPE will be explored in detail.

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