Development of engineering design competencies using TELE-EDesC: Do the competencies transfer?

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Abstract – **In this paper we investigate if a technology enhanced learning environment for engineering design competencies can promote transfer of these competencies. We developed TELE-EDesC, a self-learning technology enhanced learning environment to teach Structure Open Problem competency, one of the first competencies used in the engineering design thinking process. TELE-EDesC contains learning activities and instructional scaffolds that have been known to promote transfer. In this study, students worked with TELE-EDesC learning activities in the topic of analog electronics. The two-part study investigated if: i) students can acquire Structure Open Problem competencies by learning with TELE-EDesC, and ii) the TELE-EDesC (experimental group) students can transfer these competencies by structuring a new open design problem in a new topic in analog electronics. Analysis of students' solutions demonstrated that students who learnt with TELE-EDesC scored higher on a posttest that measured Structure Open Problem competencies than students in a control group. Further, TELE-EDesC helped students transfer some competencies to the new topic, but they struggled to transfer competencies involving higher order cognitive skills.**

Keywords-engineering design; thinking skill; engineering design competency; technology-enhanced learning; transfer

I. INTRODUCTION

An important objective of engineering education is that in addition to content, students should be able to develop and apply various cognitive, or thinking skills, such as problem formulation and problem solving, creation and revision of scientific models, data analysis and interpretation, design of real world systems and so on [1]. One such important cognitive skill is engineering design thinking. Engineering design is a systematic and thoughtful process, in which "designers generate, evaluate, and specify concepts for devices, systems, or processes" [2]. It is a complex, ill-structured problem solving process. Many universities teach engineering design such as via project-based learning [3], case study method [4] or reverse engineering [5]. Yet numerous reports have shown that graduating engineers lack engineering design skills [6] and teaching engineering design thinking is reported to be difficult [2]. Hence there is a need for interventions to help students learn engineering design thinking.

Researchers and educators have utilized the affordances of ICT based teaching-learning environments to help students develop various thinking skills such as science inquiry and experimentation [7], argumentation [8], systems thinking and modelling [9] and so on. While the use of technology is common in engineering design, engineering design thinking has not been directly addressed in technology enhanced learning environments, especially for students' self-learning.

In this paper we present our research on the development of a technology enhanced learning environment for engineering design competencies, TELE-EDesC (pronounced Tele-Desk). We operationalized engineering design thinking in terms of measurable learning outcomes, or competencies, and designed learning activities in TELE-EDesC to address these competencies. In prior work, we have reported studies of students' acquisition of engineering design competencies and their behaviour as they interact with TELE-EDesC [10]. This study focuses on students' transfer of engineering design competencies to a new context. Transfer is one of the most common goals that educators aspire towards. It has been a fundamental goal of education throughout history [11]. Along these lines, the motivation of this study is to investigate the extent to which students who learn with TELE-EDesC can apply the learned design competencies beyond the initial learning context.

II. BACKGROUND AND RELATED WORK

A. Engineering design thinking

Engineering design has been defined from a variety of perspectives. Some consider design thinking as a set of critical steps to be followed, others perceive it as a problem solving activity [12]. The process of engineering design thinking has been defined as a systematic and intelligent decision-making process through which products or artefacts are generated [2]. Engineering design thinking has also been operationalized in terms of the development of various competencies such as problem definition, problem scoping, information gathering, convergent and divergent thinking, idea generation, implementation, process improvement and communication [2,12]. Researchers have conducted studies with experts to identify engineering design competencies [13]. While different researchers and educators may use different terminologies, a common set of design competencies emerges from different approaches. These competencies include: structuring open problem, information gathering, divergent and convergent thinking, and creating, interpreting and using multiple representations.

B. TEL environments for thinking skills

In the past two decades, technology enhanced learning (TEL) environments have become an integral part of the teaching-learning process. They have been known to enhance traditional instruction and improve students' conceptual understanding. In science and engineering domains, learning from such interactive visual environments offers several benefits such as, practise 'what-if' scenarios, promote learners' analytical skills, improve procedural knowledge, foster explanation and argumentation skills, build mental models, increase learner engagement, and so on. [14]. TEL environments have gone beyond specific domain knowledge and have addressed pan-domain cognitive or thinking skills such as science modeling skills [9] and virtual experimentation [15]. The learning components of such TEL environments include inquiry and modeling tools via interactive simulations, opportunities for experimentation and metacognitive scaffolds. Many TEL environments above address open-ended problem solving tasks, but specific competencies related to engineering design, or structuring of open problem are not targeted explicitly.

C. Theoretical underpinnings of transfer

Traditionally, transfer has been considered as an independent application of knowledge and skills acquired in one situation into another [16]. This approach, termed as 'Direct Application' has been criticized because of its narrow criteria for successful transfer measured by performance on sequestered problem solving [11], as well for its view of knowledge as a static entity [17]. A more current approach to understanding transfer is 'Preparation for Future Learning' [16] which is a broader approach focusing on students' abilities to learn in new contexts. The new context is not isolated, and can involve supports that help the learner perform the task in the new situation. This approach considers learning to be active and constructive. In this 'Preparation for future learning' approach, metacognitive skills play an important role. To promote transfer, teaching-learning environments need to support constructive learning processes, enhance students' self-regulation, and should encourage students to use their knowledge and skills productively and consciously [11].

III. TELE-EDesC LEARNING ENVIRONMENT

A. Objectives of TELE-EDesC

The main objective of TELE-EDesC is that students should be able to develop engineering design thinking. We operationalize engineering design thinking in terms of measurable competencies [10] and its sub-competencies. In this paper, we focus on the competency of 'Structure Open Problem', which is a key competency for engineering design since substantial part of design activity is devoted to structuring and formulation of problem [18]. Structuring the problem is one of the first tasks involved in design thinking and poor structuring of problem has led to poor design of artefacts [13].

The competency of 'Structure open problem' (SOP) is operationalized into four sub-competencies: Student should able to i) identify specifications in open-ended problem (SOP1), ii) use specifications to structure problem (SOP2) , iii) sequence steps of design process to (SOP3) and iv) write structured problem statement (SOP4). Each sub-competency is considered to be a learning objective of TELE-EDesC.

B. Basis of TELE-EDesC pedagogical design

TELE-EDesC contains learning activities, instructional prompts, and scaffolds that trigger design thinking process among learners. To develop the learning activities and other pedagogical features in TELE-EDesC, we first analyzed the cognitive processes that need to be triggered to attain the sub-competencies of Structure Open Problem. We found that certain common cognitive processes that need to be triggered while structuring the open problem. These cognitive processes are: Decision-making, concept integration and synthesis. We then decided the learning activities and features in TELE-EDesC that trigger the above cognitive processes to perform the tasks required to attain the Structure Open Problem sub-competencies. These learning activities and features were based on recommendations from instructional design principles and cognitive science theories for triggering the cognitive processes of decision-making, concept integration and synthesis.

The cognitive process of decision-making is triggered by scaffolding mechanisms such as task-problematizing [19] and help students to articulate their thinking [20]. Decision making can be triggered using reasoning questions and providing options for selecting decisions. To trigger students' concept integration, opportunities were provided for experimentation and reflection. Instructional design principle of pre-training [21] were used to create learning activities for concept integration. To trigger students' cognitive process of synthesis, metacognitive scaffolds such as self-regulation and formative assessment have been recommended [22].

C. Learning activities and features of TELE-EDesC

To trigger decision making cognitive process, TELE-EDesC contains question prompts to provide opportunity for learners to reflect on their thinking process [22]. The question prompts are designed in the form of guided activities with explanatory feedback and are referred to as *decision making tasks* (Fig 1). Question prompts appear at the design stage where students need to make a decision, for example, on which device to choose, or which circuit might be appropriate. Each option that students choose leads to feedback, not only of whether the students' decision was appropriate, but also with explanations and examples of why the decision may not be the best in the given situation. Thus students are explicitly led through the decision making process, several times in each TELE-EDesC module.
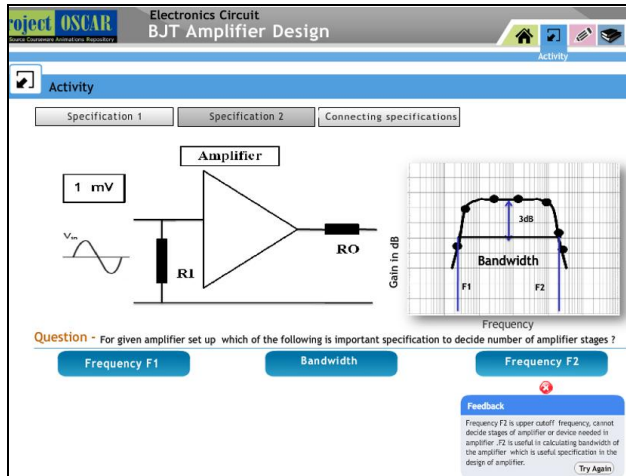
Figure 1. TELE-EDesC learning activity: *Decision making task* with explanatory feedback

An important TELE-EDesC learning activity that promotes concept integration is *concept enforcement questions*, which are based on the principle of pretraining [21]. These are formative assessment questions that elicit concepts related to the design problem. Multiple choices given to students address misconceptions or relate to prior knowledge. Explanatory feedback is provided for association of knowledge. Opportunity for guided experimentation is provided by *simulative manipulations.* Students are allowed to select different parameters of design and changes are shown as graphs or waveforms.

Synthesis cognitive process requires decision making and concept integration as well as application of both simultaneously in an embedded manner. To ensure that students do so, TELE-EDesC contains *information agents*, that provide information and appear on demand from user, and *capsule recommendations* which are design scaffolds in the form of summary statements.

IV. RESEARCH METHOD

The research goal of this study is to investigate if engaging students in the process of engineering design thinking via a technology enhanced learning environment can lead to acquisition and transfer of Structure Open Problem design competencies. The research questions are:
RQ1: Does the process of engaging in TELE-EDesC learning activities affect students' acquisition of Structure Open Problem design competencies?
RQ2: Do students who learn with TELE-EDesC transfer the design competencies to a new situation?

A. Participants

The participants in this study were 51 students from second year electronics engineering major from two colleges (referred to as College-A and College-B) in an urban area in India. All students were familiar with the topic in TELE-EDesC, as they had learnt it in the theory course on the same topic in the previous semester. However they were not exposed to engineering design in this topic. Students were familiar with ICT-based learning materials such as interactive simulations. However they were mostly used to learning from lectures and by doing homework problems, and were not used to self-learning.

For the first part of the study (RQ1), participants were divided in two groups. Students from College-A (N=23) were considered to be the experimental group and students from College-B (N=28) were considered to be the control group. Both colleges belong to Mumbai University, hence there is an enormous uniformity (dictated by the norms of the university) in the teaching, learning and assessment patterns. The two colleges are known to be similar in terms of entry profile of the students, courses offered and exams. To further examine the statistical equivalence between the two groups, an independent sample t-test was conducted to test for differences in students' previous semester's marks in Analog Electronics course. No statistically significant difference was found ($p > 0.05$), indicating equivalence between the groups. The second part of the study (RQ2) included only experimental group students (College A).

B. Procedure

The first part of the study (RQ1 - acquisition of engineering design competencies) involved a quasi-experimental research design with the following steps:
1. *Initial learning:* Both groups learned in self-study mode using their respective learning materials. Experimental group students learned with the activities in TELE-EDesC, in which they went through the process of structuring an open design problem in the topic of amplifier design. Control group students learned with material in the same topic but in the format of *informative visualizations,* which was in the format of a slides containing text, diagrams and animations, but without the TELE-EDesC features of decision making task questions, simulative manipulation and so on. Both groups were given 40 minutes to work with the material.
2. *Testing for competency acquisition:* Students in both groups took a 'Competency Acquisition' test for 30 minutes. The test involved a paper & pencil task of structuring an open problem in the same topic. However the problem details, such as the specifications of the circuit to be designed were different than the ones they had encountered in the initial learning step.

The second part of the study (RQ2 - transfer of competencies) involved the following steps:
1. *Learning of new topic:* Students (from experimental group only) were given leaning material in the topic of DC circuit design. The new learning material was in the form of slides with diagrams and explanation of decision steps (i.e. not as a TELE-EDesC module). Students were not familiar with design of circuits in this topic. Students studied the material for 30 min.
2. *Testing for transfer:* The same students were given a paper & pencil 'Transfer' test in which they had to structure an open problem in the new topic they had just studied, DC circuits.

C. Instrument and analysis

To assess students' development of Structure Open Problem competencies, we used assessment rubrics that had been validated [11]. The rubrics criteria are based on the sub-competencies of SOP competency. Each rubric item is assessed on a scale of 0 to 4 indicating different performance levels. 0 -'missing', 1 - 'inadequate' performance, 2 - the performance 'needs improvement' and 3 - 'target performance'. The performance levels are descriptive. The rubrics for SOP competency contain four items (rows), one for each SOP sub-competencies.

These rubrics were used to score students' responses to the Competency Acquisition test in which they had to structure the open problem and write a problem statement. The frequency distribution of rubrics scores was calculated for each sub-competency. Since the rubrics scores are ordinal data, the medians for the two groups were calculated and the difference of the two groups was tested using a Mann-Whitney U test.

V. RESULTS

To answer RQ1, students' rubrics score on the Competency Acquisition test was compared. Table I shows the frequency distribution of students achieving scores of 0,1,2 and 3 respectively in each SOP sub-competency for the control group and Table II shows the corresponding data for the experimental group.

TABLE I.   FREQUENCY DISTRIBUTION OF STUDENTS ON COMPETENCY ACQUISITION TEST SCORES: CONTROL GROUP (N=28)

Rubrics Scores	0	1	2	3
SOP1 – Identify specifications	2	16	7	3
SOP2 – Use specifications	3	22	2	1
SOP3 – Sequence steps of design	5	21	0	2
SOP4 – Write structure statement	5	17	4	2

TABLE II.   FREQUENCY DISTRIBUTION OF STUDENTS ON COMPETENCY ACQUISITION TEST SCORES: TELE-EDESC GROUP (N=23)

Rubrics Scores	0	1	2	3
SOP1 – Identify specifications	0	5	3	15
SOP2 – Use specifications	0	9	0	14
SOP3 – Sequence steps of design	0	5	4	14
SOP4 – Write structure statement	0	7	2	14

Table III shows the results of the Mann-Whitney U-test to determine if there was a difference in the rubrics scores between the two groups.

TABLE III.   MANN-WHITNEY U-TEST COMPARISON OF RUBRICS SCORES OF ON COMPETENCY ACQUISITION TEST

SUB-COMPETENCY	U	Z SCORE	P-VALUE
SOP1 – Identify specifications	132	-3.58	<0.001
SOP2 – Use specifications	133	-3.56	<0.001
SOP3 – Sequence steps of design	84.5	-4.49	<0.001
SOP4 – Write structure statement	123.5	-3.75	<0.001

The Mann Whitney U test showed a significant difference at p<0.001 level between the two groups for all sub-competencies related to Structure Open Problem.

To answer RQ2, that is, can the TELE-EDesC students transfer SOP competencies to a new context, their responses on the Transfer test was scored using the same rubrics. Table IV shows their scores.

TABLE IV.   FREQUENCY DISTRIBUTION OF STUDENTS WITH DIFFERENT RUBRICS SCORES ON TRANSFER TEST: TELE-EDESC GROUP

Rubrics Scores	0	1	2	3
SOP1 – Identify specifications	1	6	0	16
SOP2 – Use specifications	1	8	1	13
SOP3 – Sequence steps of design	1	11	0	11
SOP4 – Write structure statement	2	13	1	7

To test for transfer, we compared Transfer test scores (Table IV) with Competency Acquisition test scores (Table II). The number of students getting scores of 0, 1, 2 and 3 look comparable on all sub-competencies except SOP4. Since scores in these tests are from a paired sample, we conducted a Wilcoxon signed rank test for difference in median scores. We found there was no statistically significant difference on SOP1, SOP2 and SOP3. However, for SOP4, students' transfer test score was lower than the competency acquisition test score (Z= - 2.35, p= 0.018, N=23) and the difference was statistically significant at p <0.05 level.

VI. DISCUSSION AND CONCLUSION

To answer RQ1, our study shows that process of engaging in TELE-EDesC learning activities helps students' acquire Structure Open Problem design competencies. According to the results in Tables I-III, students who learn with TELE-EDesC outperform the equivalent group students on their ability to structure open ended problems. TELE-EDesC students' scores on the Competency Acquisition test was higher than the scores of the control group who learnt the same topic for the same time but in a different format. The difference in scores was statistically significant for all structure open problem sub-competencies. This leads us to conclude that the learning activities and pedagogical features in TELE-EDesC (Section IIIC) had an effect on trigger necessary cognitive processes required for learners to acquire Structure Open Problem design competencies.

To answer RQ2, we examine the performance of TELE-EDesC students on the Competency Acquisition test and the Transfer test. Students wrote the Competency Acquisition test after working with TELE-EDesC learning activities in the same topic. Then they studied material via slides containing text and diagrams on the new topic. Finally students wrote the transfer test, in which they structured a new open design problem. Tables II & IV and the subsequent tests of statistical significance show that students' rubrics score was the same in the new topic for sub-competencies SOP1 – identify specifications, SOP2 – use specifications to structure the problem and SOP3 –

sequence the steps of design process. Since students were not trained with TELE-EDesC for the new topic, that is, they did not explicitly do learning activities to structure an open problem in the new topic, we conclude that they were able to do so because they transferred the SOP competencies they had acquired from the first topic. However students performed poorly on SOP4 – write structured problem statement on the new topic, that is, they were not able to transfer this sub-competency.

What could have led to students' acquisition and transfer of structure open problem competency? Why were they not able to transfer some of the sub-competencies to the new topic? We address these questions by examining the question prompts and instructional scaffolds present in TELE-EDesC. The inclusion of such scaffolds has been recommended to promote students learning of not only conceptual and procedural knowledge, but also flexible thinking skills [21]. The learning activities in TELE-EDesC, which contain the above prompts and scaffolds were carefully designed to trigger cognitive processes of decision-making, concept integration and synthesis. It is necessary that these cognitive processes be triggered in the learner so that they can perform tasks related to solve open design problems. For example, *decision making tasks* not only helped the learner make correct decisions in the given problem, but the prompts and feedback in it helped them identify important decision points. TELE-EDesC leads students through the decision making process many times, thereby helping to internalize the thinking process so that they can apply it in the novel situation.

The sub-competency of 'write structured problem statement' requires the cognitive process of synthesis, which is a higher order cognitive skill. Metacognitive strategies are highly recommended to promote synthesis. Students should be given an opportunity to plan, monitor, evaluate, revise and reflect [23]. TELE-EDesC contains some metacognitive strategies and scaffolds such as explanatory feedback and opportunities to revise decisions. Students are also provided summary statements. However, what is currently missing are explicit reflection prompts and activities. This lack could have led to an inability to perform the synthesis level task of writing the structured problem statement in the new topic.

One way to provide more opportunities for students to evaluate and reflect on their work is via self-assessment. This is one direction of future work. Another is to include social supports, such as means for interaction and collaboration which are also recommended to be effective in the design technology enhanced learning environments.

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