# Self-assessment rubrics as metacognitive scaffolds to improve design thinking

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**Abstract:** An important goal of engineering education is to develop design thinking competency among students. These competencies include: structuring open problem, information gathering, divergent and convergent thinking, and multiple representations. We have developed Engineering Design Interactive Visualizations (EDIVs), a technology-enhanced learning environment for students' self-learning of engineering design competency. The EDIVs contain activities to promote decision-making, concept integration and overall synthesis, which are necessary cognitive mechanisms to attain design competencies. However, in addition to cognitive strategies, students require metacognitive scaffolds to help them reflectively and mindfully apply these strategies to new contexts. Hence, we included self-assessment rubrics in EDIVs to act as metacognitive scaffolds for the process of design. In this paper, we describe the role and structure of self-assessment rubrics for the engineering design competency of Structure Open Problem, and report results of an experiment where students worked with EDIVs in two conditions – with and without rubrics. We find that the rubrics prompt students to perform formative assessment of their own performance, and correct themselves if necessary, thus leading to improved performance in a new design problem.

**Keywords:** Design thinking competency, Technology enhanced learning environment, interactive visualization, scaffolding, metacognition, self-assessment

## 1. Introduction and related work

The development of design thinking ability is an important goal of engineering education. Professional organizations, accreditation bodies (ABET, 2014) as well as educators (Sheppard, 2003) have emphasized that graduating students should be able to design effective solutions for given needs. However, design thinking is complex and teaching design is difficult (Dym, 2005). Efforts to teach engineering design thinking mainly include stand-alone design courses based on a version of project-based learning (Dutson et.al, 1997). These courses have been reported to be beneficial to students, especially in promoting student interest and retention (Wood et.al., 2001). Challenges have been reported too in running such courses, such as extra faculty time, special training, and lack of assessment techniques. Thus design courses are not common in universities, which translate into lack of design ability among students (May & Strong, 2006).

The above problems are compounded in part because of the lack of a unique definition of what comprises engineering design thinking. Plenty of definitions and perspectives abound (Atman et.al, 1997; Crain et.al, 1995). What is common in all approaches is that engineering design is a systematic and thoughtful process, in which "designers generate, evaluate, and specify concepts for devices, systems, or processes" (Dym, 2005). The designed artifacts must satisfy specifications and constraints in order to meet the user's requirements. For example, in electronics system design, in order to design function generators, one needs to consider the type of waveforms, amplitude and frequency range etc. as specifications. Based on these definitions, we take a competency-based approach, and envisage the design thinking process in terms of a set of engineering design competencies that need to be developed and applied while solving design problems. These competencies include structuring open problem, information gathering, divergent and convergent thinking, and multiple representations.

In recent years, the affordances of ICT has led to the development of technology enhanced learning (TEL) environments to promote various thinking skills. There exist numerous TEL systems for modeling ability such as WISE (Linn et. al. 2003) and Co-Lab (van Joolingen et. al., 2005), scientific argumentation (Scheuer et. al, 2009 contains many examples) and designing virtual experiments (Hemlo, Nagarjan & Day, 2002), but fewer for engineering design thinking. We have developed Engineering Design Interactive Visualizations (EDIV), a TEL environment for students' self-learning of engineering design competencies.

In a prior experimental study (Mavinkurve & Murthy, 2012), we have investigated the effectiveness of EDIVs that target Structure Open Problem competency. We have shown that students who learnt with EDIV were able to develop certain sub-competencies such as identifying specifications in an open problem, and were able to apply them to a new design problem. However, students did not satisfactorily demonstrate the development of sub-competencies such as being able to synthesize and write a structured problem statement in the context of the new problem. Subsequent interviews with students revealed that they are often not aware of the cognitive processes that need to be performed at a particular time that would have led to the development of this sub-competency. Unlike experts, novice students have not internalized these cognitive processes. Hence they need to reflectively abstract these processes from the learning context, and mindfully apply them to the new context (Perkins & Salomon, 1992).

In this paper, we focus on the problem of helping students to reflectively and critically apply cognitive processes needed to write a structured statement for a given open design problem. One strategy to help students achieve this is to include metacognitive scaffolds. The inclusion of scaffolds for complex tasks has been recommended to promote students learning of not only conceptual and procedural knowledge, but also flexible thinking skills (Reiser 2004; Etkina et. al., 2010). Scaffolds can promote students' metacognitive thinking, which includes planning, monitoring, evaluating, revising and reflecting (Jacobs & Paris, 1987). Metacognitive thinking is a crucial component for design activities (Davidowitz & Rollnick, 2003). Scaffolds that promote metacognitive thinking help students learn from the experience so that they can apply knowledge and skills in new contexts.

To provide metacognitive scaffolds for design thinking, we added formative assessment rubrics in the EDIVs (Section 2). These rubrics allow students the opportunity of self-assessment, which is a powerful way of implementing formative assessment (Black & Wiliam, 1998). The rubrics provide students feedback on their responses to the EDIV activities so that they can monitor their learning process themselves with respect to the learning goals. At the same time, they focus students' attention on the important cognitive processes needed for accomplishing the complex task at hand. Thus the inclusion of the rubrics are intended to develop students' design competencies. In Section 3, we report results of an experiment where students worked with EDIVs in two conditions – with and without rubrics, and discuss the role of self-assessment rubrics in developing students' design thinking.

## 2. Learning Environment: Engineering Design Interactive Visualization

The process we followed to develop the leaning environment for various design competencies involved the following steps: i) identify and operationalize specific measurable units of the competency (which we refer to as 'sub-competencies'), ii) analyze the cognitive tasks that need to be performed to attain the sub-competencies, and iii) decide features and activities in the EDIVs that trigger students' cognitive mechanisms to perform these tasks. In this section, we discuss the design of EDIVs that target the competency of 'Structure Open Problem', which is one of the first tasks involved in design thinking (Sheppard, 2003).

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). To attain each sub-competency above, students need to perform a set of cognitive tasks. For example, to be able to identify relevant specifications needed to structure open problem (SOP1), the set of cognitive tasks to be performed are: identification of all possible specifications, deciding relevant specifications and interpretation of chosen specifications with respect to the concepts. When these tasks for all sub-competencies were analyzed, we found that there are three common cognitive mechanism required to execute these tasks: A. Decision making, B. Concept integration and C. Synthesis.

**A. Decision making mechanism**. Decision making process is defined as mentally generating possible options for given situation and evaluating options based on set of information (Gresch & Bögeholz, 2012). Decision making is a process that all designers have to engage in throughout the design process (Dym, 2005). It involves an iterative series of divergent-convergent thinking in which students need to generate many options based on the set of information available, evaluate them based on domain knowledge expertise. Decision making is an essential triggering cognitive mechanism in the attainment of SOP1 (identification of specification) and SOP2 (use of specifications), as both these competencies require students to think of multiple options and select appropriate ones. Each EDIV contained activities and features which trigger the above cognitive mechanisms. Decision making can be triggered using question prompts (Ge & Land, 2005) as well as providing opportunity for knowledge integration through experimentation and reflection (Etkina et. al., 2010). To trigger this cognitive mechanism, we added 'Decision Making Task Questions' with multiple options and formative feedback. The EDIVs also contained simulative manipulation activity (Chen et.al., 2011) in which students are provided variable manipulation for experimentation, followed by questions with feedback on students' responses. This provides opportunity for reflection. Fig. 1 shows a Decision Making Task Question activity in which students have to make decisions about the selection of specifications. Fig. 2 shows a simulative manipulation activity related to selection of amplifier circuit to satisfy specifications.

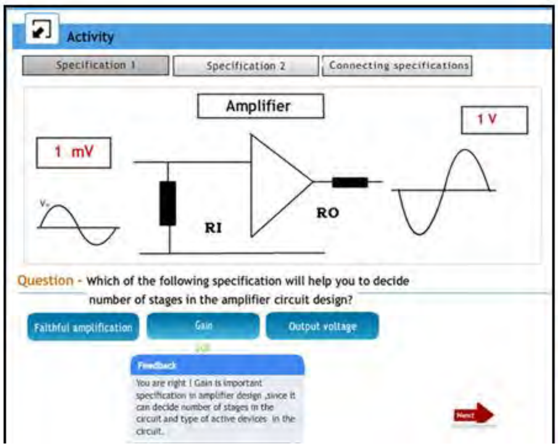


Fig.1. Decision Making Task Question activity

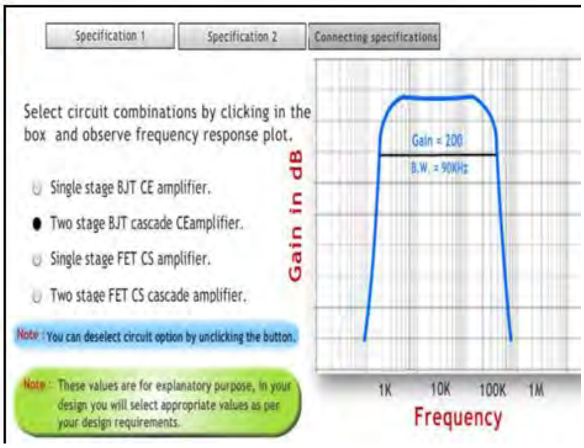


Fig.2. Simulative Manipulation activity

**B. Concept Integration mechanism**. This is the process of connecting various concepts using information association and knowledge integration (Aurisicchio et.al, 2007). The cognitive mechanism of concept integration expects students to associate different pieces of information based on domain knowledge. This is mainly required for SOP3 (sequence decision steps) wherein students should able to recall and connect appropriate concepts based on domain knowledge. Concept integration also requires knowledge of multiple representations with visual thinking. The third major cognitive mechanism, synthesis forces student to think about entire system. Concept integration primarily expects information association activity, for which the EDIVs contain Concept Enforcement Questions (CEQ) questions In addition, EDIVs contain controlled animation with dynamically linked representations to help students to associate information. To trigger system thinking process, EDIVs contain information agents like design tips and information box along with Decision Making Task Questions and Concept Enforcement Questions.

**C. Synthesis mechanism.** Synthesis can be defined as integration of all the cognitive mechanisms mentioned above and monitoring of the achievement of these mechanisms (Dym, 2005). Synthesis is required to attain SOP4 (write structured problem), as an entire system-level thinking is required for this sub-competency, including decision making with appropriate concept integration. To trigger system thinking, EDIVs should be able to provide opportunity to monitor learning process. This can be achieved through metacognitive strategies which were added in EDIVs via self-assessment rubrics, based on the scientific abilities rubrics (Etkina et. al., 2006). These rubrics are descriptive rating scales which consist of pre-established criteria to evaluate student's performance on each design sub-competency. The rubrics for the sub-competencies related to Structure Open Problem competency are shown in Table1. After activities such as Decision Making Task Questions and Concept Enforcement Questions, students are provided the relevant rubric items. Since the rubrics contain descriptors not only of the target performance level, but also of non-ideal performance, they prompt students to carry out formative assessment of their own performance in the activity, and correct themselves if necessary. This helps students not only to monitor their level of achievement of cognitive task, but also plan learning based on expected target level.

Table 1: Rubrics items for various sub-competencies of Structure Open Problem competency

| Design sub-competency | Target performance | Needs improvement | Inadequate | Missing |
|---|---|---|---|---|
| **Is able to extract required relevant specifications from given open ended problem** | All relevant visible and hidden specifications are identified and interpreted accurately. No irrelevant specifications identified. | An attempt is made to identify specification Most of them identified but few hidden ones missing or needs more interpretation. | An attempt is made but specifications identified are most of them are wrong or irrelevant or incomplete. | No attempt is made to extract specifications |
| **Is able to structure open problem using specifications** | Specifications are used to identify interconnections of the system in order to structure problem. | An attempt is made to use specifications but minor specifications are not used, or used incorrectly. | An attempt is made to use specifications but required specifications not used or wrongly applied. | No attempt is made to use specification to structure problem |
| **Is able to sequence the design steps based on specifications** | All major and minor design steps are identified and sequenced correctly based on specifications. | Most designs steps are sequenced correctly. Few steps are missing or not sequenced correctly. | Design steps are not sequenced at all or not based on specifications. | No attempt is made to write design steps. |
| **Is able to write structured design problem statement** | Problem statement is written clearly including details of specifications and design steps. | Problem statement is written clearly but few minor details are missing. | Problem statement is not written clearly but scattered information is available. | No attempt to write coherent statement. |

## 3. Evaluating effectiveness of self-assessment rubrics in EDIVs

### *3.1 Method*

In a prior study (Mavinkurve & Murthy, 2012) we had shown that features of EDIVs to promote decision making and concept integration (such as decision making task questions, simulative manipulation, concept enforcement questions etc) led to the improvement of design sub-competencies of SOP1, SOP2 and SOP3. Here, we report a two group quasi-experiment to investigate the importance of including self-assessment rubrics as metacognitive prompt in the EDIVs, which targets SOP4 (write structured problem statement) via the cognitive mechanism of synthesis. The two conditions in the experiment were the presence or absence of self-assessment rubrics in the EDIV.

*Participants*. The study participants were students from 2nd year Electronics Engineering (N=45) major. Students were familiar TEL environments, as well as with the content in the EDIV, as they had learnt it in the theory course. However, they were not exposed to design in this topic.

*Procedure*. Students were randomly assigned to two groups. The experimental group consisted of 23 participants, control group had 22 participants. The equivalence between the groups was tested on basis of their previous semester's grades and no statistically significant difference was found between them ($t=-0.08$, $p=0.9$). Two sets instructional materials on the topic of amplifier design from electronics domain were developed. The experimental group received an EDIV which contained self-assessment rubrics. The control group received the same EDIV but without the self-assessment rubrics. Students in both groups studied their material for 30 minutes, after which they attempted the post-test. The post-test contained an open design question on a topic related to (but not the same as) the instructional material for which students had to describe (on paper) their design.

*Instrument*. To assess the development of students' design competencies we used assessment rubrics, similar to the self-assessment rubrics as shown in Table 1. These rubrics were validated prior to the experiment. Inter-rater reliability was found to give 86% agreement between 3 instructors.

### *3.2 Results*

The scores on the post-test are ordinal data, hence we used a Mann-Whitney U-test for analysis. The mean ranks for each sub-competency for the two groups are shown in Table 2. The results show that the mean ranks for the experimental group are higher in each sub-competency. However, the difference was statistically significant only for SOP3. We further analyzed the data by categorizing students based on SOP sub-competency scores. Students who scored 0 or 1 were categorized as 'unsuccessful' on the design task and students who scored 2 or 3 as 'successful' on the design task. For each sub-competency we calculated the number of students from the control and experimental group in the successful and unsuccessful categories respectively. We used the Statistical Attribute Tracking (SAT) diagram (Majumdar & Iyer, 2014) to represent and analyze the data (Fig. 3).

Table 2: Comparing SOP sub-competency scores of experimental and control group

| Sub competency | Group | N | Median | Mean Rank | z | p |
|---|---|---|---|---|---|---|
| SOP1 | Control | 22 | 2 | 20.162 | 1.4 | 0.15 |
| | Expt | 23 | 2 | 25.72 | | |
| SOP2 | Control | 22 | 2 | 20.48 | 1.24 | 0.21 |
| | Expt | 23 | 2 | 25.41 | | |
| SOP3 | Control | 22 | 2 | 19.61 | 1.9 | 0.056 |
| | Expt | 23 | 3 | 26.67 | | |
| SOP4 | Control | 22 | 1 | 19.84 | 1.56 | 0.11 |
| | Expt | 23 | 3 | 26.02 | | |

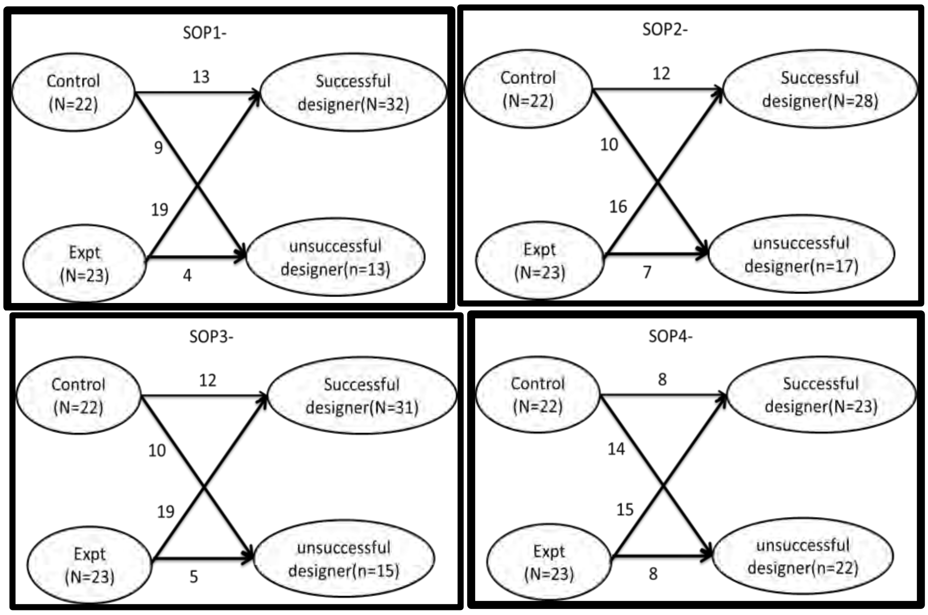


Fig.3. Stratified Attribute Tracking Diagram for successful and unsuccessful design

We found that for the sub-competencies of 'identify specifications in open problem' (SOP1), 'use specifications to structure problem' (SOP2) and sequence steps of design process (SOP3), more number of students fall in successful designer category than the unsuccessful category for both control and experimental groups. Since both groups worked with the basic design thinking activities in EDIVs, this confirms our previous results that EDIVs are useful to develop these sub-competencies. To examine the role of self-assessment rubrics, we compared the number of students in the successful designer category from the control and experimental groups. We found that majority of students in the successful designer category are from experimental group (e.g. 19-expt. group, 13-control group for SOP1). For the sub-competency of 'write structured problem statement' (SOP4), we found that equal number of students lie in successful and unsuccessful categories respectively. But in the successful designer category, majority students were from experimental group (15) compared to control group (8). This indicates that addition of self-assessment rubrics guides students towards successful design.

Following the post-test, we conducted interviews with 5 students from the experimental group. The interview questions focused on which activities students preferred while learning with EDIV and why. Here, we show a quote from a student which indicates students' perceptions of how self-assessment rubrics helped: "*If I know what is wrong in my answer and how I can achieve score 3, it helps me in learning, as most of the time we don't know what is wrong in my answer*".

## 4. Discussion and Conclusion

The sub-competency of writing structured problem statement from open problem requires students to perform synthesis operation by integrating various decisions and concepts. Attainment of this sub-competency leads to the overall goal of structuring of open problem, which is a key step in the engineering design process. The self-assessment rubrics trigger the process of synthesis by providing students metacognitive scaffolds in the form of the description of the target performance as well as lower levels of performance. They prompts students to carry out formative assessment of their performance, monitor and revise their achievement level and plan their learning based on target level.

Design tasks are open ended and the development of design thinking involves complex cognitive processes. The EDIV activities such as decision making task questions, concept enforcement questions, and simulative manipulation trigger students to perform the cognitive processes involved in design thinking. Self-assessment rubrics provide students the opportunity for thoughtful reflection and improvement of their work in these activities. The rubrics help simplify the complex design tasks by providing transparent criteria of evaluation to students. In future work, we will include self-assessment rubrics as an integral part of EDIVs to help students to engage in system thinking and to monitor the essential cognitive processes of design thinking.

## References


ABET (2014). ABET criteria for accrediting engineering programs. http://www.abet.org/eac-criteria-2014-2015/

Atman, C. J., Chimka, J. R., Bursic, K. M., & Nachtmann, H. L. (1999). A comparison of freshman and senior engineering design processes. Design Studies, 20(2), 131-152.

Aurisicchio, M., Ahmed, S., & Wallace, K. M. (2007). Improving design understanding by analyzing questions. In ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 307-317). American Society of Mechanical Engineers.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. Assessment in education, 5(1), 7-74.

Chen, Y. L., Hong, Y. R., Sung, Y. T., & Chang, K. E. (2011). Efficacy of simulation-based learning of electronics using visualization and manipulation. *Educational Technology & Society*, 14 (2), 269–277.

Crain, R. W., Davis, D. C., Calkins, D. E., & Gentili, K. (1995). Establishing engineering design competencies for freshman/sophomore students. In Proceedings of Frontiers in Education Conference, Vol. 2, 4d2-1.

Davidowitz, B., & Rollnick, M. (2003). Enabling metacognition in the laboratory: A case study of four second year university chemistry students. Research in Science Education, 33(1), 43–69.

Duston, A. J., Todd, R. H., Magleby, S. P., & Sorensen, C. D. (1997). A review of literature on teaching engineering design through project-oriented capstone courses. Journal of Engineering Education, 86(1).

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. Journal of Engineering Education, 94(1), 103-120.

Etkina, E., Van Heuvelen, A., White-Brahmia, S., Brookes, D. T., Gentile, M., Murthy, S., Rosengrant, D. & Warren, A. Developing and assessing student scientific abilities. Physical Review Special Topics, Physics Education Research, 2, 020103.

Etkina, E., Karelina, A., Ruibal-Villasenor, M., Rosengrant, D., Jordan, R. and Hmelo-Silver, C. E. (2010). Design and reflection help students develop scientific abilities: Learning in introductory physics laboratories. Journal of the Learning Sciences, 19(1), 54 – 98.

Gresch, H. & S. Bögeholz, (2012). Identifying non-sustainable courses of action: A prerequisite for decision-making in education for sustainable development. Research in Science Education, 1-22.

Hmelo, C. E., Nagarajan, A., & Day, R. S. (2002). It’s harder than we thought it would be: A comparative case study of expert-novice experimentation. *Science Education, 86*(2), 219–243.

Linn, M. C., Clark, D., & Slotta, J. D. (2003). WISE design for knowledge integration. Science Education, 87(4), 517–538.

Majumdar, R. & Iyer, S. (2014). Using stratified attribute tracking (SAT) diagrams for learning analytics. IEEE 14th International Conference on Advanced Learning Technologies (ICALT), 7-10 July 2014.

May, E. & Strong, (2006). D. S. Is engineering education delivery what industry requires? The Third CDEN Design Conference; Toronto, Ontario, Canada; 2006.

Mavinkurve, M., Murthy, S. (2012). Interactive Visualizations to teach design skills. 20th International Conference on Computers in Education, ICCE 2012, Singapore.

Perkins, D. N., & Salomon, G. (1992). Transfer of learning. International encyclopedia of education, 2.

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. Journal of the Learning Sciences, 13, 273–304.

Sheppard, S. D. (2003). A description of engineering: An essential backdrop for interpreting engineering education. Proceedings (CD), Mudd Design Workshop IV, Claremont, Cal.: Harvey Mudd College.

Scheuer, O., Loll, F., Pinkwart, N., & McLaren, B. M. (2010). Computer-supported argumentation: A review of the state of the art. International Journal of Computer-Supported Collaborative Learning, 5(1), 43–102.

van Joolingen, W. R., de Jong, T., Lazonder, A. W., Savelsbergh, E. R., & Manlove, S. (2005). Co-Lab: research and development of an online learning environment for collaborative scientific discovery learning. Computers in human behavior, 21(4), 671-688.

Wood, K. L., Jensen, D., Bezdek, J., & Otto, K. N. (2001). Reverse engineering and redesign: Courses to incrementally and systematically teach design. Journal of Engineering Education, 90(3), 363-374.

Xun, G. E., & Land, S. M. (2004). A conceptual framework for scaffolding III-structured problem-solving processes using question prompts and peer interactions. Educational Technology R&D, 52(2), 5-22.