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A Performance-Based Evaluation Rubric for Assessing and Enhancing Engineering Design Skills in Introductory Engineering Design Courses*

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Using the developmental research methodology, this study develops a performance-based evaluation rubric that can assess and enhance students' engineering design skills in introductory engineering design courses. The effectiveness of the proposed performance-based evaluation rubric was validated in the context of engineering design activities for students and practical directions for instructors to evaluate student performance. The proposed rubric included four phases, namely the problem, the solution, implementation, and process management, based on seven performance criteria and 21 measureable scales.

Keywords: engineering design skill; engineering design assessment; evaluation rubric; performance-based evaluation

1. Introduction

Introductory design courses have been developed to enhance students' motivation for engineering, increase student retention, and gain basic design skills [1]. Many studies have reported that introductory engineering design courses have positive effects on students' intellectual development, retention, and motivation for upper-division courses [2–5]. In the early 1990s, introductory engineering design courses have been introduced to engineering colleges in South Korea by the Accreditation Board Engineering Education of Korea. According to Taurasi (2007), about 65% of all engineers from mechanical, applied, and manufacturing engineering firms surveyed agreed on a need for today's engineers to be more creative and innovative to be globally competitive Because the need for creativity in engineering emphasizes creativity in engineering design activities [6], the introductory engineering design course in Korea is entitled "Creative Engineering Design," and many engineering educators have made efforts to prepare and teach this subject.

Engineering educators must be able to develop students' design skills and assess their skills appropriately through engineering design courses. One important issue in teaching introductory design courses is the assessment of students' engineering design capability. In addition, many engineering educators have difficulty assessing students' design skills, and students struggle with engineering design projects because of a lack of clear guidelines. A few assessment methods such as student portfolios, verbal protocol analyses, and the "Creative Engineering Design Assessment" (CEDA) method have been used to evaluate students' design achievement and processes [7–10]. These methods focus on evaluating students' design competencies and processes from instructors' point of view but do not fully guide students' design activities. Further, there is a well-established method for assessing and enhancing students' design skills. This study develops a performance-based evaluation rubric that can assess and enhance students' engineering design skills and can be used in introductory engineering design courses. In particular, the literature on general characteristics, important issues, and assessment methods for introductory engineering design courses is reviewed to establish some directions for developing a rubric. The developed performance-based evaluation rubric is applied to introductory engineering design courses, and its feasibility and effectiveness are validated.

2. Theoretical background

2.1 Introductory engineering design

Engineering design reflects a systematic, intelligent generation, and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints [11]. According to the ABET, "engineering design is a decision-making process, in which the basic sciences, mathematics, and engineering sciences

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are applied to convert resources optimally to meet a stated objective'' [12].

Introductory engineering design courses focus more on conceptual design methods and less on discipline-specific artifacts [13]. First-year students can be guided to perform reasonable conceptual design without detailed technical knowledge. Marra, Palmer and Litzinger (2000) found the introductory engineering design course at Penn State University to be a project-focused, active course requiring students to work in teams and interact with instructors to solve open-ended problems based on the design process [5]. The first-year engineering design course in the department of mechanical engineering at Stanford University was found to give students exposure to the creative nature of engineering through design projects, hands-on laboratory exercises, and open-ended problem solving [14]. A creative engineering course at Sungkyunkwan University was found to provide learning opportunities during the pursuit of design solutions through collaborative efforts of design teams as well as innovative and effective design ideation methods and design presentation skills [15]. According to the definition of engineering design and an overview of introductory design courses, introductory engineering design can be defined as suggesting creative conceptual solutions for open-ended problems through engineering design processes [16]. In summary, three issues in engineering design activities include the design problem, the design process, and the design output (type) [17], and the next section addresses these issues in detail.

2.2 Three issues: The problem, the process, and the output

2.2.1 Design problem

Kaufmann (1988) defined a ''problem'' as a gap between the current and desired states [18]. The definition of a problem should have at least three characteristics: The problem exists in the current state with particular givens such as circumstances, objects, or pieces of information; the desired state requires pondering to transform the current state into the desired state; and there is no direct and obvious way to solve the problem [19]. Many engineering education researchers have agreed that design problems are open-ended and ill-structured [11, 20]. When a design problem is initiated, the goals are usually vague, and constraints and criteria need to be clarified. These problems cannot be resolved mechanically or automatically by using known methods, and there are a considerable number of solutions [16]. In an introductory engineering design course, students should conduct engineering design processes to solve ill-structured and ill-defined design problems, and these problems must be associated with daily life [21].

To define a design problem, students have to actively analyze needs of target users and gather information from experts, patent databases, or electronic databases. Students look for underlying needs by observations, interviews, or survey methods and search for sufficient information on the initial problem, such as patents, products, or professional knowledge to analyze reasons and identify design requirements and constraints. Design requirements are objectives that should be ultimately satisfied. Design constraints reflect a number of limitations on conditions under which the development of a system takes place, such as forms, functions, technologies, budgets, and time periods.

2.2.2 Design process

Introductory engineering design courses typically focus on producing conceptual solutions, and therefore engineering design processes are generally recognized according to the following steps: problem recognition or understanding → information gathering → problem analysis → idea generation → idea evaluation → validation → communication [1, 16, 22, 23]. Introductory engineering design activities can be classified into three types according to two variables: whether to suggest a design problem and whether to provide information or knowledge needed to solve a problem [24]. The first type is ''guided engineering design,'' in which core concepts or knowledge is learned through lectures before design activities start and design problems are provided by instructors. The second type is ''engineering design by problem-based learning,'' in which a design problem is presented by instructors but students have to learn core concepts or knowledge needed to solve the problem by themselves. Finally, the third type is ''engineering design by self-directed learning,'' in which students have to find a design problem as well as learn core concepts or knowledge to solve the problem through self-directed learning. Despite the importance of problem finding [25], engineering educators have focused mainly on solving problems in introductory design courses and on making design problems. Most design processes or creativity support tools guide students to generate possible solutions, but they do not identify new problems [26]. In the present study, the emphasis is placed on engineering design activities of the third type. That is, students are guided to find their own design problem and learn information or knowledge related to it by themselves.

2.2.3 Design output

Design outputs result from the engineering design process and are normally documented in models, drawings, engineering analyses, and other documents. Pahl and Beitz (1984) offered three types of design outputs [27]: First, "original design" aims to create an original solution principle for a system with the same, similar, or new task. Second, "adaptive design" is for adapting known solution principles to satisfy new tasks. Finally, "variant design" varies certain aspects of the system, leaving function and solution principles unchanged. These different design types are clearly related to the design process, and therefore an introductory engineering design focusing on conceptual design can be classified as original design. Therefore, the output of original design should be original (new idea) and applicable (useful) [17, 28]. In engineering design, patentability is a generally acceptable perspective when evaluating the design output. A design must satisfy the following criteria to produce a patent [29]: (1) it is new in that the design output has never been released to the public, (2) it is capable of industrial application, and (3) it involves an inventive step. Because freshman and sophomore engineering students may have difficulty achieving technical completeness, the design output should be assessed in terms of whether the solution for the initially stated problem is novel and applicable in a real setting [16].

2.2.4 Assessment of engineering design skills

Although previous assessments have typically relied on team grades on design reports, a team's performance in terms of design artifacts, and the team's ability to answer design questions on tests [30], various approaches have been considered to assess engineering design skills. Assessment techniques can be classified into quantitative and qualitative assessment tools. Because of characteristics of engineering design skills, qualitative assessment techniques have been applied and developed to assess design skills in introductory engineering design courses.

The major qualitative assessment techniques applied to introductory design courses include verbal protocols, interviews, and documents [31]. In verbal protocols, by collecting and analyzing verbal data on the cognitive processing of design activities, students are monitored and asked to think aloud during design activities. Several studies have analyzed verbal protocols to identify important factors in engineering design [32–34]. Interviews have also been used to obtain in-depth information on students' design activities. Marra, Palmer, and Litzinger (2000) used the interview technique to examine the effects of first-year design courses on engineering students' intellectual development [5]. Documents can include portfolios, concept maps, and paper-based assessment tools. A portfolio is a collection of students' work over time and is used to holistically assess student learning. Olds and Pavelich (1996) suggested that portfolios can be integrated into engineering design activities [9]. Concept maps have been applied to assess students' design knowledge by asking them to draw a concept map of the design process at the beginning and end of first-year design courses [35]. Although it is clear that the concept map technique is an effective tool for assessing students' integrated design knowledge, it is difficult to be used as an evaluation tool.

Some researchers have developed paper-based assessment tools to evaluate students' design skills. Baily, Szabo, and Sabers (2004) used analytical writing to assess design knowledge by asking students to critique two ill-structured design processes [30]. Frank, Strong, Boudreau, and Pap (2009) developed a paper-based design skill assessment method in which students are provided open-ended engineering scenarios and asked to outline the process they follow to solve a problem [36]. Charyton and Merrill (2009) developed the "Creative Engineering Design Assessment" (CEAD) method [8], in which students are asked to sketch designs that incorporate one or several three-dimensional objects, to list potential users, and to perform problem finding as well as problem solving in response to specific functional goals. These document methods are assessed using analytic rubrics.

Feasible quantitative techniques include self-assessment and test methods. Gintili et al. (1999) used a self-assessment method to measure students' perceived growth in terms of their design capability and a self-assessment instrument consisting of seven categories, including information gathering, problem definitions, idea generation, evaluation/decision making, implementation, teamwork, and communication [37]. Okudan, Ogot, Zappe, and Gupta (2007) developed the "Comprehensive Assessment of Knowledge on Engineering Design," which can be used as a pretest/posttest instrument for assessing the knowledge level in engineering design [38]. This instrument consists of 20 questions designed to measure skills and concepts that can be taught in introductory engineering design courses.

These existing assessment tools suggest some important practical implications for assessing students' engineering design skills in various ways. Most qualitative methods can be costly and time consuming if they are used only when instructors evaluate students' capability. Therefore, this study develops an evaluation rubric that can guide team-based engineering design activities as well as assess students' engineering design skills.

3. Directions for design assessment

3.1 Three phases of engineering design

The purpose of an introductory engineering design course is to enhance the student's engineering design skills through engineering design activities to make conceptual solutions based on an engineering design process for open-ended and ill-structured problems. The core learning outcomes of introductory engineering design courses include engineering design skills. Engineering design activities are usually team-based, and with the consideration of this characteristic, teamwork and communication skills are secondary learning outcomes. Therefore, this study develops a rubric that can evaluate the following three learning outcomes: engineering design, teamwork, and communication skills.

The engineering design process can be classified into three phases: (1) the problem phase, (2) the solution phase, and (3) the implementation phase. In the problem phase, students identify and analyze a problem and finally define a design problem including design requirements and constraints. Students investigate prior art and related information, analyze causes of the problem, and define the problem through the process of problem recognition, information gathering, and problem definitions. A team project proposal can be an evaluation tool in the problem phase. In the solution phase, students develop several possible solutions for the defined problem through the use of creative idea generation methods and select optimal solutions. A midterm report and a peer evaluation can be evaluation tools in the solution phase. The selected solution is evaluated in terms of its originality and applicability. In the implementation phase, students develop a prototype of the selected solution and verify its compliance with design requirements and constraints. In addition, they write a final report for their whole design process and make a presentation. A final report, a presentation, and a peer evaluation can be evaluation tools in the implementation phase.

3.2 Performance criteria and tasks

To evaluate performance in terms of accomplishing learning objectives of three phases (e.g., problem, solution, and implementation phases), performance criteria should be established. Performance criteria should specify observable details that evidence the desired state [1]. Performance tasks are goal-directed activities completed by students and then judged by instructors based on specific performance criteria. The introductory engineering design process generally consists of eight steps. Table 1 shows the performance criteria and tasks for each step.

3.3 Scoring scales

Scoring scales are necessary for determining student performance relative to the desired level of achievement. In this study, a four-point scoring scale was used (1: poor; 2: marginal; 3: satisfactory; 4: excellent). This four-point scoring scale was used because most evaluators tend to give average scores. In this scale, 1 represents a low level (i.e., a student not satisfying most of the performance criteria); 2, a marginal level (a student partially satisfying performance criteria for each design step); 3, a satisfactory level (a student satisfying performance criteria for each design step); and 4, a high level (a student exceeding performance criteria set for the introductory design course). Table 2 shows the scoring scales for idea generation in the solution phase.

4. Validation of the performance-based evaluation rubric

The performance-based evaluation rubric (hereafter "the PBER") for introductory engineering design courses was validated using three different methods based on Tracey and Richey (2007): an expert review, a usability test, and a field evaluation [39]. These three validation methods were used to find implications for modifying the PBER as well as to validate its effectiveness in guiding or assessing students' design activities. More specifically, the first expert review was conducted to validate the developed PBER. A usability test was conducted for the instructor to examine the effects of the PBER and obtain opinions on the rubric after its classroom use. The second expert review was conducted to verify the modified PBER based on the first review. Finally, a field evaluation was employed to investigate the effectiveness of the PBER as guidelines for students' engineering design activities.

4.1 Expert review

4.1.1 Procedures and participants

Ten experts participated in expert reviews to validate the PBER. All were engineering professors who taught introductory engineering design courses more than three times. The expert group included two civil engineering professors (A and B), two geoinformatic engineering professors (C and D), one mechanical engineering professor (E), one industrial engineering professor (F), one chemical engineering professor (G), one architectural engineering professor (H), and two material engineering professors (I and J). The purpose of the PBER research and development was introduced to seven experts (A, B, C, E, F, G, and J), and these individuals were invited to participate in an expert review. In addition, an expert review instrument was

Table 1. Performance criteria and tasks for engineering design skills

Phases	Steps	Performance criteria	Performance tasks
Problem	Problem recognition	Students can identify open-ended, challenging, and impactive design problems	Determination of open-ended , challenging, and impactive design problems
	Information gathering	Students can survey and analyze related information for a design problem	A needs analysis Information investigation
	Problem definition	Students can define design problems, including design requirements and constraints	A gap analysis Problem definitions Requirements and constraints
Solution	Idea generation	Students can develop several possible solutions for design problems by applying creative idea generation methods with team members	The climate and attitudes Creative methods The number of ideas
	Optimal solution selection	Students can select optimal solutions from several possible solutions based on their originality and applicability	Idea evaluation Originality Applicability
Implementation	Solution improvement	Students can elaborate on selected optimal solutions with drawings or prototypes	Prototypes Completeness /punctuality
	Validation	Students can verify the compliance of selected solutions with design requirements and constraints	Requirements Constraints
	Presentation and reporting	Students can effectively deliver engineering design processes and their results with writings and words	Structures and fidelity Speaking, listening, and responding

Table 2. Scoring scales for the idea generation step

Scales	Poor 1	Marginal 2	Satisfactory 3	Excellent 4
Climate and attitudes	The team atmosphere was critical and stifling, and students did not actively participate in team work.	Students respected other members' opinions but did not suggest their own ideas.	Students were willing to suggest their own creative ideas and encouraged and supported other members' opinions.	Students actively suggested their own creative ideas and motivated and stimulated other members' opinions.
Creative methods	Students did not use any creative idea generation methods.	Students developed their solutions with one creative idea generation method.	Students developed their solutions with two creative idea generation methods.	Students developed their solutions with three or more creative idea generation methods.
Quantity	Students did not develop any possible solutions for a defined problem.	Students developed one possible solution for a defined problem.	Students developed two possible solutions for a defined problem.	Students developed three or more possible solutions for a defined problem.

provided and collected by e-mail for the other three experts (D, H, and I) after a brief introduction to the purpose of the PBER research and development by phone.

4.1.2 Instrument and analysis

The instrument for the expert review was designed to evaluate the appropriateness of the proposed PBER by using a four-point Likert-type scale. The instrument was composed of 28 items: one item for the appropriateness of dividing engineering design activities into three phases (problem, solution, and implementation phases), three items for the appropriateness of a stepwise design process for each phase, eight items for the appropriateness of performance criteria for each phase, eight items for the appropriateness of evaluation items for each phase, and eight items for the appropriateness of rating criteria for each phase. These experts were asked to comment on these items if they had any. The expert review instrument was circulated within the expert group to verify its understandability and improve its validity based on comments raised by the expert group.

The validity of expert responses was analyzed using the content validity index (CVI) and the inter-relater agreement (IRA) adopted in Rubio et al. (2003) [40]. The CVI is the number of experts evaluating each item as valid divided by the total number of experts. The CVI provides a ratio of experts assessing items to be valid, and a CVI > 0.80 is considered valid. The IRA gives a score for the trustworthiness of experts' evaluation and is calculated by dividing the number of items evaluated equally by the total number of items. An IRA > 0.80 is considered valid. In this study, CVI and IRA scores were measured on a four-point Likert-type scale: "strongly disagree" (1), "disagree" (2), "agree" (3), and "strongly agree" (4).

4.1.3 Results of an expert review

According to the expert review of the PBER, the average score was 3.65 (out of 4.0), and all CVI and IRA values for each item exceeded 0.8 (Table 3). These results indicate all elements of the PBER to be highly valid and reliable. However, the rating criteria for information gathering (experts C and I) and idea generation (experts B and C) were evaluated as inappropriate because of their mechanical judgments. In addition, those items in the PBER were evaluated as appropriate by most experts, and therefore its appropriateness was reexamined through a usability test and a field evaluation.

4.2 Usability test

4.2.1 Procedures and participants

A usability test was conducted to assess the effectiveness of the PBER and identify possible improvements from instructors after their use of the PBER in their introductory engineering design courses. Three experts (expert B, who participated in the expert review, K, and L) who conducted introductory engineering design courses at I university in Korea in the spring semester of 2013 participated in the usability test. The purpose of the study and the PBER were explained to these three experts, who were asked to provide the PBER to students and use it for evaluating team projects at the end of semester. In the introductory engineering design course, students learned about the engineering design process and employed various creative thinking techniques during the first half of the semester. Then they carried out team projects until the end of the semester. Problems in team projects were not suggested by instructors, but students actively found uncomfortable things in their daily lives through team activities.

4.2.2 Instrument and analysis

The instrument in the usability test was composed of three parts. The first part included five items for the usability of the PBER from the instructor's point of view. The second part included eight items to investigate the instructor's perception of the educational effectiveness of the PBER in each design stage. The third part included three open-ended items to find the PBER's strengths, weaknesses, and possible improvements.

The test items to measure the usability of the PBER from the instructor's point of view were adopted from Lee and Jin (2014) [16] and modified to accommodate the purpose of the present study. Five items asked about the efficiency, effectiveness, generality, learnability, and satisfaction of the PBER. To verify the educational effectiveness of the PBER as a guide for a creative engineering design process, eight items were derived to assess the helpfulness of the PBER to the design process. A total of 13 items were reviewed by experts (M and N) with Ph.D. degrees in education and teaching experience in introductory engineering design courses. Responses to the questionnaire were presented along with items, and collected data from open-ended items were grouped by considering the theme of opinions.

4.2.3 Results of the usability test

Table 4 shows the responses of three instructors to the usability test. The results show that the instructors were satisfied with the PBER in terms of its above-average efficiency, effectiveness, generality, learnability, and satisfaction. In addition, the instructors recognized the PBER to be very helpful for guiding students in relevant activities through engineering design stages.

With respect to the items for strengths of the PBER, expert B reported that the PBER presented required activity levels and content and had educational effectiveness, showing the student the overall engineering design process. Expert K responded that the PBER enables a quantitative and objective evaluation based on the rubric in each design stage instead of on some rough and qualitative evaluation criteria. According to expert L, students can apply the PBER to other design activities even after the introductory engineering design course. This implies that the PBER can be generalized to evaluate engineering design activities.

In terms of the items for shortcomings and weaknesses, expert B suggested that the PBER should be improved to allow for a sufficient evaluation of project quality because it was observed that

Table 3. Review results for the structure and components of the PBER and the validity of expert responses

		Expert responses											
Items		**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**CVI**	**IRA**
Three phases		4	4	3	4	3	4	3	4	4	3	1	1
Learning objectives	Problem phase	4	4	3	3	3	4	4	4	4	4	1	
	Solution phase	4	4	3	3	4	4	4	4	4	4	1	
	Implementation phase	4	4	4	3	4	4	4	4	4	4	1	
Design process	Problem phase	4	3	3	3	3	4	3	4	3	3	1	
	Solution phase	4	4	4	4	4	4	4	4	4	4	1	
	Implementation phase	4	4	4	4	4	4	4	4	4	4	1	
Problem recognition	Performance criteria	4	3	4	3	3	4	4	4	4	4	1	1
	Evaluation items	4	3	4	3	3	4	4	4	4	4	1	
	Rating criteria	4	3	4	2	4	4	4	4	4	4	0.9	
Information gathering	Performance criteria	4	4	3	3	4	4	4	4	4	4	1	1
	Evaluation items	4	3	3	3	4	4	4	3	3	4	1	
	Rating criteria	4	3	2	3	4	4	4	3	2	4	0.8	
Problem definition	Performance criteria	4	4	3	3	3	4	4	4	3	4	1	1
	Evaluation items	4	3	3	3	3	4	4	4	3	4	1	
	Rating criteria	4	3	3	3	3	4	4	4	4	4	1	
Idea generation	Performance criteria	4	4	3	3	3	4	4	4	4	4	1	1
	Evaluation items	4	3	3	3	3	4	4	3	3	4	1	
	Rating criteria	4	2	2	3	3	4	4	3	3	4	0.8	
Optimal solution selection	Performance criteria	4	4	3	3	3	4	4	4	4	4	1	1
	Evaluation items	4	3	3	3	3	4	4	4	3	4	1	
	Rating criteria	4	3	3	3	3	4	4	4	4	4	1	
Solution improvement	Performance criteria	4	4	3	3	3	4	4	4	4	4	1	1
	Evaluation items	4	4	3	3	3	4	4	4	3	4	1	
	Rating criteria	4	4	3	3	3	4	4	4	4	4	1	
Validation	Performance criteria	4	4	3	3	3	4	4	4	4	4	1	1
	Evaluation items	4	3	3	3	3	4	4	4	4	4	1	
	Rating criteria	4	3	4	3	3	4	4	4	4	4	1	
Presentation and reporting	Performance criteria	4	4	4	3	4	4	4	4	4	4	1	1
	Evaluation items	4	4	4	3	4	4	4	3	3	4	1	
	Rating criteria	4	4	4	3	4	4	4	4	4	4	1	

Table 4. Experts’ responses to the usability test questionnaire

		Instructors’ responses		
	Items	**B***	**K***	**L***
Usability of the PBER	Efficiency	4	5	5
	Effectiveness	4	5	5
	Generality	4	5	5
	Learnability	4	5	5
	Satisfaction	4	5	5
Learning effectiveness of the PBER	Problem recognition	4	4	4
	Information gathering	4	4	4
	Problem definition	4	4	5
	Idea generation	3	3	4
	Optimal solution selection	4	4	5
	Solution improvement	4	4	5
	Validation	4	4	5
	Presentation and reporting	4	4	5

* Three experts who participated in the usability test (see Section 4.2.1).

some students tried to satisfy quantitative criteria such as numbers of ideas and solutions without considering this quality only to secure full credit. Given this suggestion, rating criteria for information gathering and idea generation were amended to allow for a qualitative evaluation.

Expert K suggested the separation of activities related to the design process from those related to the management of design projects. In the solution improvement stage under the implementation phase, the completeness and punctuality of performance tasks were the items evaluated through the engineering design process. Therefore, a new item "design process management" was included to implement the suggestion of expert K.

Expert L agreed that the problem definition needed to follow the recognition of the problem and the gathering of relevant information in the problem phase. After using the original rubric, however, he suggested that problem recognition and information gathering needed to be combined to enhance the effectiveness of the PBER because a problem can be found through information-gathering activities and various solutions to a particular problem can be provided. To reflect the suggestion by expert L, problem recognition and information gathering in the problem phase were combined in the PBER. Given the suggestions by the three experts participating in the usability test, the original PBER was enhanced and updated.

A second expert review was conducted to validate the appropriateness of the improved PBER (see Appendix 1: The modified PBER). Four experts (expert B, K, and L, participants in the usability test, and professor M, a civil engineering specialist with 16 years of teaching experience) participated in the second expert review. The initial expert review instrument was modified to reflect the updated rubric. The instrument was received by e-mail from experts B, K, and L. The research purpose and process were introduced to expert M in person, and the expert review instrument was provided and collected by e-mail. According to the results of the second expert review, the average score was 3.77 (out of 4.0), and all CVI and IRA values for each item were 1, indicating that all PBER elements were highly valid and reliable.

4.3 Field evaluation

4.3.1 Participation

The purpose of the field evaluation was to identify the educational rationale for the PBER. To reveal the practical applicability of the PBER as a guide for students' design activity, a field evaluation can be essential. A total of 77 undergraduate students (64 males) enrolled in introductory engineering design courses at I University participated in this study. The experiment was conducted as part of the students' regular coursework.

4.3.2 Study design and procedures

The students were randomly assigned to the experimental and control groups. Their motivation and knowledge of the design process in the introductory engineering design course were pretested to verify the homogeneity of each group. Based on the pretest, two groups were considered homogeneous. Based on the developed PBER, information on engineering design processes and activities that needed to take place at each stage was provided to all students, who completed their exercises in the classroom for the given case study. Team projects were assigned to each group. The developed PBER was provided to the experimental group but not to the control group for the team project. The introductory engineering design course entailed the following activities: an introduction to the subject and a pretest in the first week; instructions for the engineering design process and team-based exercises between week 2 and week 8; team projects between week 9 and week 13 (students actively work as a group to follow the engineering design process, including problem, solution, and implementation phases); the team project presentation between week 14 and week 15; and information obtained from students through a survey in week 16.

4.3.3 Measures

The following variables were measured: the study time per week, study efforts, learning outcomes for engineering design skills, and student satisfaction. The study time per week was assessed using one item (multiple choice) covering five alternatives (less than 3 hours per week (1) over 12 hours per week (5)). Study efforts were assessed using one item based on a five-point Likert-type scale ranging from "extremely low" (1) to "extremely high" (5) [41]. The scales for assessing engineering design skills were developed based on performance criteria for each process of the PBER and consisted of seven items ($a = 0.89$). The scales for perceived student satisfaction were developed by referring to those items in Arbaugh (2000) [42]. Perceived student satisfaction was assessed using three items ($a = 0.86$), including "I was satisfied with this course" and "My choice to take this course was a wise one." In addition, seven items ($a = 0.85$) were developed to assess the helpfulness of the PBER for managing activities in the overall engineering design process and the sixth stage of the engineering design process. These items were designed for the experimental group to assess the learning effectiveness of the PBER. Perceived engineering design skills, perceived student

Table 5. Descriptive statistics for dependent variables for two groups

Dependent measures	Treatment			
	Experiment group (n = 39); control group (n = 38)			
	M (SD)	*M* (SD)	*t* value	*d*
Study time per week[a]	2.84 (0.85)	2.36 (0.63)	2.511*	0.77
Study efforts	4.00 (0.70)	3.75 (0.69)	1.376	
Perceived engineering Design skills	4.20 (0.62)	3.74 (0.66)	2.844**	0.70
Perceived student satisfaction	4.24 (0.62)	4.01 (0.70)	1.268	

[a] (1) Less than 3 hours; (2) 3 ~ 6 hours; (3) 6 ~ 9 hours; (4) 9 ~ 12 hours; (5) over 12 hours.

satisfaction, and learning effectiveness for the PBER were measured using a five-point Likert-type scale ranging from "strongly disagree" (1) to "strongly agree" (5). Two experts (M and N) who participated in the usability test examined the validity of the developed items.

4.3.4 Analysis

The collected data were analyzed through an independent samples t-test to determine the impact of the PBER in the context of introductory engineering design courses. The dependent measures included the study time, study efforts, the development of engineering design skills, and student satisfaction. Effect size was measured using Cohen's d if a significant effect was found. Effect size was interpreted as follows: small <0.2, moderate ~0.5, and large >0.8 [43]. A basic statistical analysis was conducted for the learning effectiveness of the PBER targeting the experimental group.

4.3.5 Results of the field evaluation

As shown in Table 5, the mean values for the experimental group (with the PBER) were higher than those for the control group in terms of the study time per week, study efforts, perceived engineering design skills, and perceived student satisfaction. In particular, the independent samples t-test revealed significant effects on the study time per week (M = 2.84, SD = 0.85 vs. M = 2.36, SD = 0.63, d = 0.77) and perceived engineering design skills (M = 4.20, SD = 0.62 vs. M = 3.74, SD = 0.66, d = 0.70), and here the effect size was moderate. These results demonstrate that those students exposed to the PBER invested more time in performing team-based design projects and were more likely to perceive the PBER to increase their performance in activities in each engineering design stage. According to the students' perception of the learning effectiveness of the PBER (Table 6), the PBER was helpful for student activities and could be used as a useful guide for successful engineering design activities.

5. Discussion

5.1 Theoretical contributions

Education-related evaluation methods used in a specific course generally entail objective-based evaluation techniques to determine the level of student achievement in terms of learning objectives [44]. Therefore, many studies have focused mainly on evaluating the level of engineering design skill acquired by students [8, 36, 38]. The objectives of this educational evaluation or assessment were to verify the level of student achievement in terms of learning goals while reflecting evaluation results to improve students' competency and educational quality. In this regard, this study provides instructors with objective criteria for assessing students' engineering design skills along with scaffolding students during engineering design activities. The proposed rubric can provide students with a clear level of the instructor's expectations to increase their performance in areas such as engineering design skills. This result provides support for Reddy and Andrade (2010), who suggested that the rubric can promote learning as well as help teachers evaluate student performance [45]. The PBER can help students guide engineering design activities by specifically stating a desired performance level in engineering design. Scaffolding has been defined as a learning strategy supporting learners by limiting the complexity of the learning

Table 6. Students' perception of the learning effectiveness of the PBER

	Items	M	SD
Learning effectiveness of the PBER	Problem recognition	4.12	0.72
	Problem definition	4.04	0.61
	Idea generation	3.96	0.61
	Optimal solution selection	4.16	0.47
	Solution improvement	4.00	0.64
	Presentation and reporting	4.16	0.68
	Design process management	4.12	0.60

context [46]. Among the four types of scaffolding suggested in Hannafin, Hannafin, Land, and Oliver (1997) [47], two are relevant to the PBER. First, the PBER can serve as some conceptual scaffolding to help student decide what to do at each engineering design stage. Second, it can act as a procedural form of scaffolding to help students determine which procedures they should take to solve a design problem. The results verify the usability of the PBER from the instructor's perspective in terms of its efficiency, effectiveness, generality, learnability, and satisfaction. The effectiveness of the PBER was verified based on the instructor's perception and field evaluation.

5.2 Practical contributions

The major difficulties facing instructors in managing introductory engineering design courses can be summarized into two areas: (1) monitoring and providing feedback on engineering design activities conducted through team-based project learning methods and (2) objectively evaluating engineering design processes and outcomes. Students want to receive consultation on their engineering design performance and ask for the desired level of achievement in introductory engineering design courses. In addition, because evaluation scores are not based on tests, students demand the justification of their grades on their engineering design projects. This study focuses mainly on addressing difficulties in educational settings in the real world and thus proposes the PBER to provide specific performance objectives and criteria in conjunction with specific evaluation guidelines. The results suggests that the PBER's clear specification for performance and evaluation guidelines in each engineering design process allow instructors to not only evaluate students' engineering design processes and outcomes based on objective criteria but also observe a secondary benefit of spending less time providing feedback or answers. In addition, students are clearly aware of their goals in each engineering design process to avoid any mistakes in skipping essential activities and thus can invest more time in learning to enhance their task performance.

5.3 Limitation and future directions

The participants were from two classes and divided into 10 teams. Therefore, the effectiveness of the PBER was measured based on perceived engineering design skills, perceived student satisfaction, and perceived learning effectiveness for the PBER. Future research should extend this study by analyzing the effects of the PBER on students' engineering design output. In addition, it should be useful to investigate the effects of students' self-evaluation on their engineering design outcome by using the PBER.

6. Conclusions

The present study proposes the performance-based evaluation rubric (PBER), which can support students' engineering design activities and provide practical directions for instructors to evaluate student performance. Students are expected to suggest creative conceptual solutions to open-ended problems through engineering design processes by working with team members in introductory engineering design courses. In this regard, the PBER reflects review outcomes for three issues of design programs, processes, and outputs identified in prior research on the assessment of engineering design. The results of expert reviews, usability tests, field evaluations validate the PBER for two semesters. The PBER can provide scaffolding to support students' engineering design activities and offer instructors with objective criteria for evaluating students' engineering design skills. The PBER consists of four phases, namely problem, solution, implementation, and process management phases, and include seven performance criteria and 21 measureable scales. Evaluation tools for each phase are as follows: a team project proposal for the problem phase, a progress report and a peer review for the solution phase, and a final report, a presentation, and a peer review for implementation and process management phases.

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Appendix 1. The Performance-based evaluation rubric

[Problem phase] *Learning Objectives*: Students can define problems in detail with design requirements and constraints by identifying problems and analyzing related information.

Problem recognition	*Performance criteria*: Students can set open-ended, challenging, and impactive design problems and analyze diverse information.			
Scales	**Poor** **1**	**Marginal** **2**	**Satisfactory** **3**	**Excellent** **4**
Problem finding	Students found problems based on the experience of team members.	Students found an inconvenient problem in daily life by using observations, interviews, experiences, or surveys.	Students found an inconvenient problem in daily life by using observations, interviews, experiences, or surveys under a plan.	Students found a problem valuable for improving daily life by using observations, interviews, experiences, surveys, and some other methods under a systematic plan.
Open-ended, challenging, and impactive problems	Students set problems whose level is below their capability and whose solution is self-evident.	Students set a problem whose level is below their capability and which may not have many different solutions.	Students set problems matching their capability and also had many different solutions whose effects were expected temporarily.	Students set a problem whose level was above their capability and which may had many different but useful solutions.
Information investigation	Students did not survey and analyze the set problem and related information.	Students surveyed and analyzed only accessible information through websites related to the set problem.	Students carried out a demand survey with accessible users (friends or colleagues) and surveyed part of information related to the set problem.	Students carried out a demand survey with target users, collected information (prior technologies and products), and surveyed and analyzed diverse information through interviews with related experts.
Problem definition	*Performance criteria*: Students can define design problems, including design requirements and constraints.			
Gap analysis	The current state and desirable state were not defined.	The current state and desirable state were defined, but the reason for the gap was neither presented nor clear.	The current state and desirable state were defined, and the reason for the gap was partially presented.	The current state and desirable state were defined, and the reason for the gap was analyzed from various perspectives.
Definition	The problem was not defined.	The problem was defined but vague and unclear.	The problem was clearly presented, but information on the operating zone or time of the problem was not included.	Information on the operating zone and time of the problem was clearly defined.
Requirements and constraints	Design requirements and constraints were not presented.	Only design requirements were presented.	Design requirements and constraints were defined at a proper level.	Design requirements and constraints (e.g., the economy, society, the environment, ethics, and standards) were specific and defined comprehensively.

[Solution phase] Learning objectives: Students can develop several solutions for design problems by using creative idea generation methods and select optimal solutions.

Idea generation	*Performance criteria*: Students can develop several possible solutions for design problems by applying creative idea generation methods with team members.			
Climate and attitudes	The team atmosphere was critical and stifling, and students did not participate actively.	Students respected other members' opinions but did not suggest their own ideas.	Students were willing to suggest their own creative ideas and also encouraged and supported other students' opinions.	Students suggested their own creative ideas actively and also motivated and stimulated other students' opinions.

Scales	Poor 1	Marginal 2	Satisfactory 3	Excellent 4
Creative methods	Students could generate their ideas only by team members' brainstorming.	Students generated ideas for solutions by using 2∼3 creative thinking methods, but the process was unclear.	Students generated ideas for solutions by using 2∼3 creative thinking methods, and the deduction process was clearly stated.	Students generated ideas for solutions by using various creative thinking methods, and the process was clearly stated.
Quantity	Students could not generate ideas for solutions.	Students generated ideas for solutions partially.	Students generated an optimal number of ideas for solutions.	Students generated a sufficient number of ideas for solutions from diverse viewpoints.
Optimal solution selection	Performance criteria: Students can select optimal solutions from several possible solutions based on originality and applicability.			
Idea evaluation	Students did not evaluate generated ideas for solutions.	Students selected an optimal solution through team discussions.	Students selected an optimal solution by evaluating generated ideas based on evaluation indices predetermined by team members.	Students selected an optimal solution by evaluating generated ideas in conductions with outsiders (experts and users) based on evaluation indices predetermined by team members.
Originality	The selected solution was plain and simple.	The selected solution was interesting.	The selected solution was unique and different.	The selected solution was insightful or innovative.
Applicability (*useful*)	The selected solution was not useful.	The selected solution was somewhat useful.	The selected solution was very useful.	The selected solution was indispensable.
[Implementation phase] *Learning Objectives*: Students can prepare reports and present them by using the whole design process and results after giving some shape to solutions.				
Solution improvement	*Performance criteria*: Students can elaborate selected optimal solutions with drawings or prototypes and examine whether they reflect design requirements and constraints.			
Prototype	The solution did not materialize.	Part of the final solution was materialized by drawings or prototypes.	The final solution was approximately materialized by drawings or prototypes.	The final solution materialized exquisitely by drawings or prototypes.
Correctness	There were many logical and technical problems in the final solution and prototype.	There were serious flaws in the final solution and prototype.	The final solution and prototype looked generally correct, but there were some unimportant flaws.	There was no logical or technical problem in the final solution and prototype.
Validation	The question of whether the final solution and prototype reflected design requirements and constraints was not addressed.	The final solution and prototype examined either design requirements or constraints.	The question of whether the final solution and prototype satisfied design requirements and reflected all constraints was addressed.	The question of whether the final solution and prototype satisfied design requirements and reflected all constraints was carefully addressed.
Presentation and reporting	*Performance criteria*: Students can effectively deliver engineering design processes and results with writings and words.			
Structure and fidelity	The system of the engineering design report was unclear, and the logic was lacking in its content.	The content of each label was written in detail, but the system of the whole report was insufficient.	The basic system of the engineering design report was prepared, but evidential materials for content for each label were not presented.	The system for the engineering design report was made, and evidential materials for content at each level were described faithfully.
Speaking	Students just read the presentation material without understanding the engineering design process of their own team, and therefore the delivery of their content was very poor.	Students tried to present their materials after being fully aware of the engineering design process, but their voice tone, eye contact, and gesture were not natural.	Students could present their materials by using easy terms for the engineering design process, and their voice tone, eye contact, and gesture were natural. However, they could not control the presentation time.	Students could present their materials effectively within the allowed time by using easy terms for the engineering design process, and their natural voice tone, eye contact, and gesture were appropriate.

Scales	Poor 1	Marginal 2	Satisfactory 3	Excellent 4
listening and responding	Students' manner was bad in listening to other teams' presentation, and they could not answer questions.	Students' manner was bad in listening to other teams' presentations, but they tried to answer questions.	Students listened to other teams' presentations and questions, but they could not answer questions sufficiently.	Students listened to other teams' presentations and questions and answered questions correctly.
[Process management] *Learning objectives*: Students can manage the design process systematically through collaboration with team members.				
Design process management	*Performance criteria*: Students can finish their design activities within the time appointed by managing the design process through team activities.			
Management	It was not possible to determine whether students set prior planning, and there was no record for results.	Parts of content for the prior planning of the design process and parts of records for results were left.	Students set and carried out prior planning and left records for results.	Students set and carried out phased prior planning and left records for results. They periodically examined whether each phased goal was achieved.
Teamwork	Team members were not aware of performance criteria for each design process and barely participated in design activities.	Team members were aware of performance criteria, but each focused only on his or her own duties.	Team members tried to carry out their own duties by collaborating with others.	Team members did their best to satisfy performance criteria for each design process by taking responsibility for the engineering design project and by collaborating with others.
Completeness / punctuality	Students did not submit a report.	Students completed the report generally but did not submit it by the deadline.	Students submitted reports by the deadline, but their completeness was somewhat insufficient.	Students submitted reports within the deadline, and they were sufficient.

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