Initial Development and Validation of the Self-Efficacy for Engineering Design (SEED) Survey for Undergraduate Students in Mechanical Engineering

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***Abstract*—This Work In Progress describes the development and validation of a 34-item student-focused Self-Efficacy for Engineering Design (SEED) survey. Content validity was achieved using experts' judgments. Construct validity was performed using confirmatory factor analysis (CFA). The survey validation was accomplished using 256 mechanical engineering students, distributed over three classes. The SEED survey consists of two subscales that measure the self-efficacy for (a) design competencies (SEDC) and (b) personal competencies (SEPC). SEDC consists of 8 subscales, which are (a) identifying customer needs, (b) establishing target specifications, (c) generating product concepts, (d) selecting a product concept, (e) system-level design, (f) detailed design, (g) prototyping, and (h) evaluating the design. SEPC consists of 4 subscales, which are (a) openness, (b) conscientiousness, (c) extraversion, and (d) agreeableness.**

***Keywords*— design competencies, engineering design; interpersonal competencies; intrapersonal competencies; self-efficacy**

I. Introduction

Engineering design and product development processes emphasize many common aspects, and therefore it is not uncommon to see product development used in teaching engineering design. Product development processes (PDPs) are defined as the "procedures and methods that companies use to design new products and bring them to market" [1], or "the sequence of steps or activities that an enterprise employs to conceive, design, and commercialize a product" [2]. In PDP, a process is defined as the "sequence of steps that transforms a set of inputs into a set of outputs" [2]. Several PDP models and frameworks have been proposed to help us explain and understand the design process [3], and are used across industry and academic settings [4, 5]. Examples of PDP models and frameworks include (a) the analysis, synthesis, and evaluation [6], the idea, configuration, evaluation (ICE) [7], the generate, evaluate, modify, and select (GEMS) [8], and other models such as those proposed in [9] and [6]. These models and frameworks have different perspectives for product development and each has its advantages and disadvantages. We note that although the PDP may be presented as a linear and sequential process, in reality design is a series of iterations and revisions, as ideas are tested and refined, and as new information becomes available. Product design also involves project planning and management, which are essential for accomplishing a final product in design.

One of the critical student outcomes in engineering design is self-efficacy, which focuses on measuring students' beliefs about how confident they are in accomplishing design-related tasks. Self-efficacy is strongly and positively related to learning outcomes and achievement [10, 11]. Self-efficacy is also a significant predictor of career options, especially in science and engineering college students [12, 13]. To address the need for an instrument to measure students' self-efficacy Carberry, et al. [14] developed and validated an instrument to measure students' self-efficacy in engineering design. One shortcoming in the instrument developed by Carberry, et al. [14] is that it is developed based on framework proposed by the Massachusetts Department of Education (DoE) [15] for elementary and secondary students and validated with a sample of engineers and non-engineers, professors and students, graduate and undergraduate students. Another shortcoming of the Carberry et al.'s instrument [14], is that of the 36 items used, only nine of them are self-efficacy items, corresponding to the nine engineering design tasks (one item is a general "conduct engineering design" item and eight items represent the Massachusetts DoE Science and Technology/ Engineering Curriculum Framework). The remaining items in Carberry, et al. [14] asked about motivation, success, and anxiety for the nine engineering design task, so they were not self-efficacy items.

Recognizing the limitations in Carberry, et al. [14] and realizing the need for an instrument to measure students' self-efficacy for engineering design, in addition to the need for including both personal and design competencies, led to the development and validation of the instrument reported in this paper. The focus of this paper is, thus, to develop and validate an instrument that measures undergraduate students' self-efficacy for engineering design in engineering design-related disciplines.

II. Method

A. Instrument Development

Instrument development includes: (a) identifying the content domain of the construct, (b) generating the items, and (c) constructing the instrument [16, 17]. Identifying the content domain is done by choosing the models that adequately represent the content under consideration. Generating the sample items entails writing statements that describe parts of the content. Constructing the instrument is done by making a list of the items and directions for the respondents. We designed an instrument that consists of two sections for self-efficacy for design and personal competencies.

For SEDC, we chose the Ulrich and Eppinger [2] generic Product Development Process (PDP) framework to adequately represent the content related to design competencies. We made this choice the because the Ulrich and Eppinger [2] generic Product Development Process (PDP) framework is a simple and powerful way for representing the product development process.

For SEPC, we chose the classification proposed by Pellegrino and Hilton [18] for personal competencies, which is related to personality characteristics in psychology [19-25]. Personal competencies are divided into (a) intrapersonal competencies (including openness and conscientiousness), and (b) interpersonal competencies (including extraversion and agreeableness). Openness refers to flexibility and adaptability; conscientiousness refers to promptness and timeliness; extraversion refers to qualities related to explanation and presentation; and agreeableness is related to qualities of teamwork and collaboration. The items for personality characteristics were adapted from two previously validated instruments [26, 27].

Table 1 shows the items of the SEPC and SEDC sections of SEED consecutively. Table 1 also shows the factor loadings and standard errors resulting from the Confirmatory Factor Analysis (CFA) (described below).

B. Content Validity

Content validity addresses "the degree to which items of an instrument sufficiently represent the content domain…[and] answers the question that to what extent the selected sample in an instrument or instrument items is a comprehensive sample of the content" [16]. Content validity also refers to "expert judgments of the representativeness of items with respect to the skills, knowledge, etc. domain to be covered" [28].

To assess the content validity for both the SEDC and SEPC sections of the SEED instrument, three expert judges on engineering design were solicited to rate the items for their relevance or representativeness with regard to the SEDC and SEPC sections. The three experts were professors or instructors of product development or engineering design courses, and also reported having used engineering design and product development during doctoral research. These experts also have background in educational psychology, teaching and learning in higher education, and curriculum design, so they can judge the adequacy of both engineering design items as well as personality-related items.

C. Construct Validity

Construct validity refers to the "degree of agreement with theoretical expectations" [28]. Confirmatory Factor Analysis (CFA) is almost always used during the process of scale development to examine the latent structure of an instrument [29, 30]. In our case, the SEED was developed from the existing literature in engineering design and personality characteristics. If Exploratory Factor Analysis (EFA) had been used, it would have led to exploring how many factors that the instrument would yield for the sample used. However, we are using CFA based on the assumption that the instrument leads to a structure that is conceptualized from the literature. There are two advantages for testing the construct validity using CFA based on the structure from which the instrument was conceptualized from the literature. First, this CFA testing can serve as a first step of confirming an initial structure, which can be later studied and confirmed using multiple samples and larger sample sizes. Second, the CFA testing can help in determining the factors that can be used to measure the constructs that originated from the literature, which can be helpful for studies and for curriculum that uses the same models or frameworks from the literature.

The survey validation was accomplished using 256 mechanical engineering students, distributed over three classes. The three classes consisted of 62, 103, and 81 students, who took the Engineering Design course in June, September, and December 2016, consecutively. All the students took the class for the first time. The survey was administered at the end of the semester. In general, CFA requires at large sample (preferably>= 1000) to yield conclusive results. However, our sample size ($N = 256$) relative to the size of the subscale with the maximum number of items ($q = 3$) exceeds the minimum suggested value for the ratio of sample size (N) to number of parameters to be estimated (q) [31, 32] because we treated each subscale as a separate instrument. Accordingly, the sample size was adequate, sufficient, and satisfied the $N{:}q$ hypothesis within each subscale.

First, the data-model fit indices are examined. We used the recommendations by West, et al. [33] for the indices and their associated cutoff criteria [33-35] to assess the data-model fit. Indices of goodness of fit could be divided into three categories: (a) absolute fit, (b) parsimony correction, and (c) comparative fit [36]. Absolute fit indices include: (a) χ^2, (b) SRMR, and (c) RMR. RMSEA (Root Mean Square Error of Approximation) is the most popular parsimony index. Comparative fit indices include: (a) CFI, (b) TLI, and (c) χ^2 difference. Second, localized areas of strain (which are indices that are checked to ensure they do not exceed recommended values) result from estimating the parameters of a hypothesized model.

These indices are important to check because goodness-of-fit indices may "suggest acceptable fit despite the fact that some relationships among indicators in the sample data have not been reproduced adequately" [29]. Third, the factor loadings and their associated values [29] are examined. The factor loadings and their associated values (standard errors, z-value, and p-value), we checked the following recommended values. Finally, z-score values are computed by dividing the parameter estimate by the standard error. Statistical significance was determined by $p < .05$ value (reflected by absolute value of z greater than 1.96.

III. Results

A. Content Validity

The purpose of soliciting experts' judgments was to select the items they experts agreed on for inclusion in the instrument for both the SEDC and SEPC. The SEED instrument included only the items with 100% agreement. The items that the experts did not agree on were excluded from the final instrument.

B. Construct Validity

Before estimating the parameters of CFA, the measurement model must be identified [29]. A model is identified when "on the basis of known information (i.e., the variances and covariances in the sample input matrix), it is possible to obtain a unique set of parameter estimates for each parameter in the model whose values are unknown (e.g., factor loadings, factor correlations)" [29]. All the CFA models in the SEED instrument were identified.

The goodness-of-fit indices for all the 12 subscales represented good fit, according to multiple sources [33-35, 36, 37]. First, the parsimony index: The Root Mean Square Error of Approximation (RMSEA), which should be less than 0.06, was less than 0.00. Second, the absolute index: The Standardized Root Mean Square Residual (SRMSR), which should be less than 0.08, was 0.00. Third, the comparative (relative) fit index: The Comparative Fit Index (CFI), which should be greater than 0.95) was 1.00. We note that the prototyping uses a single item, which in this case is valid because this single item measures the object of the construct [39]. The optimal values of the goodness-of-fit indices can be attributed to the simplicity of the proposed models. The proposed models are simple (each model consisting of three items and a single subscale); yet provide strong content validity, so the simplicity did not jeopardize the content of the subscales.

Modification indices (MIs) were checked. None of the MIs were above the recommended value. All factor loadings had to be larger than a cut-off value of 0.3, which was chosen to determine the salient loadings of items on factors. This condition was satisfied for all the models in the SEPC and SEDC subscales.

For the self-efficacy for personal competencies (SEPC), the four factors, along with their respective range of item loadings, include: openness (.31, .66), conscientiousness (.47, .87), extraversion (.64, .79), agreeableness (.61, .81).

For the self-efficacy for design competencies (SEDC), the eight factors, along with their respective range of item loadings, include: (a) identifying customer needs (.53, .92), (b) establishing target specifications (.65, .90), (c) generating product concepts (.72, .76), (d) selecting a product concept (.50, .90), (e) system-level design (.67, .80), (f) detail design (.52, .65), (g) prototyping (single factor), and (h) evaluating the design (.54, 84). The responses from the students in our sample to the SEED survey revealed that the items comprising the instrument clustered around factors or sub-scales that reflected the core constructs of the SEDC and SEPC.

TABLE I. Self-Efficacy For Personal Competencies ITMES

F [a]	I [b]	I am CONFIDENT that I can	FL [c]	SE [d]
Openness (OPN)	I_01	Use imagination (for design)	.66	.15
	I_02	Accept that more than one solution to a problem may be appropriate	.44	.15
	I_03	Seek different viewpoints from colleagues	.31	.23
Conscientiousness (CON)	I_04	Follow a plan accurately	.87	.13
	I_05	Assess the quality and accuracy of my work according to preset criteria	.62	.12
	I_06	Accomplish high-quality work before deadlines	.47	.11
Extra-version (EXT)	I_07	Communicate the product details in writing	.79	.09
	I_08	Present the benefits of the product to customers	.66	.09
	I_09	Explain the functions of the product to engineers	.64	.09
Agreeableness (EXT)	I_10	Work effectively and respectfully in teams	.73	.09
	I_11	Share responsibility for collaborative work	.61	.09
	I_12	Value the individual contributions made by team members	.81	.08
Identify Customer Needs (ICN)	I_13	Obtain information about constraints on the design	.92	.15
	I_14	Describe the function or use of the final product of a design task	.54	.12
	I_15	Clarify the different requirements of the design task	.53	.12
Establish Target Specs (ETS)	I_16	Clarify the different aspects (specifications) of the design task	.65	.08
	I_17	Describe design requirements using measurable specifications	.90	.06
	I_18	Describe design constraints using measurable specifications	.81	.07
Generate Product Concepts (GPC)	I_19	Integrate knowledge from multiple fields to develop a concept	.76	.07
	I_20	Use engineering knowledge to develop a concept	.73	.07
	I_21	Develop multiple suitable solutions for a design problem	.72	.07
Select Product Concept (SPC)	I_22	Compare multiple design solutions according to preset criteria	.90	.13
	I_23	Select the best design according to present criteria	.62	.11
	I_24	Use a structured process when identifying a design solution	.50	.11
System-Level Design (SLD)	I_25	Describe the components of a design concept	.80	.08
	I_26	Describe the architecture of a design concept	.73	.09
	I_27	Describe the technology of a design concept	.67	.09
Detailed Design (DLD)	I_28	Develop an experimental plan to assess a design	.65	.16
	I_29	Describe the costs of manufacturing a design	.53	.14
	I_30	Convert a selected design solution into a design plan	.52	.14
Proto-typing (PTD)	I_31	Create a prototype of the design	-	-
Evaluate the Design (ETD)	I_32	Test interaction of individual sub-components of design	.84	.10
	I_33	Use a structured process when troubleshooting problems	.74	.10
	I_34	Conduct appropriate analysis to test the function of a design	.54	.10

[a]Factor, [b]Item, [c]Factor Loading, [d]Standard Error

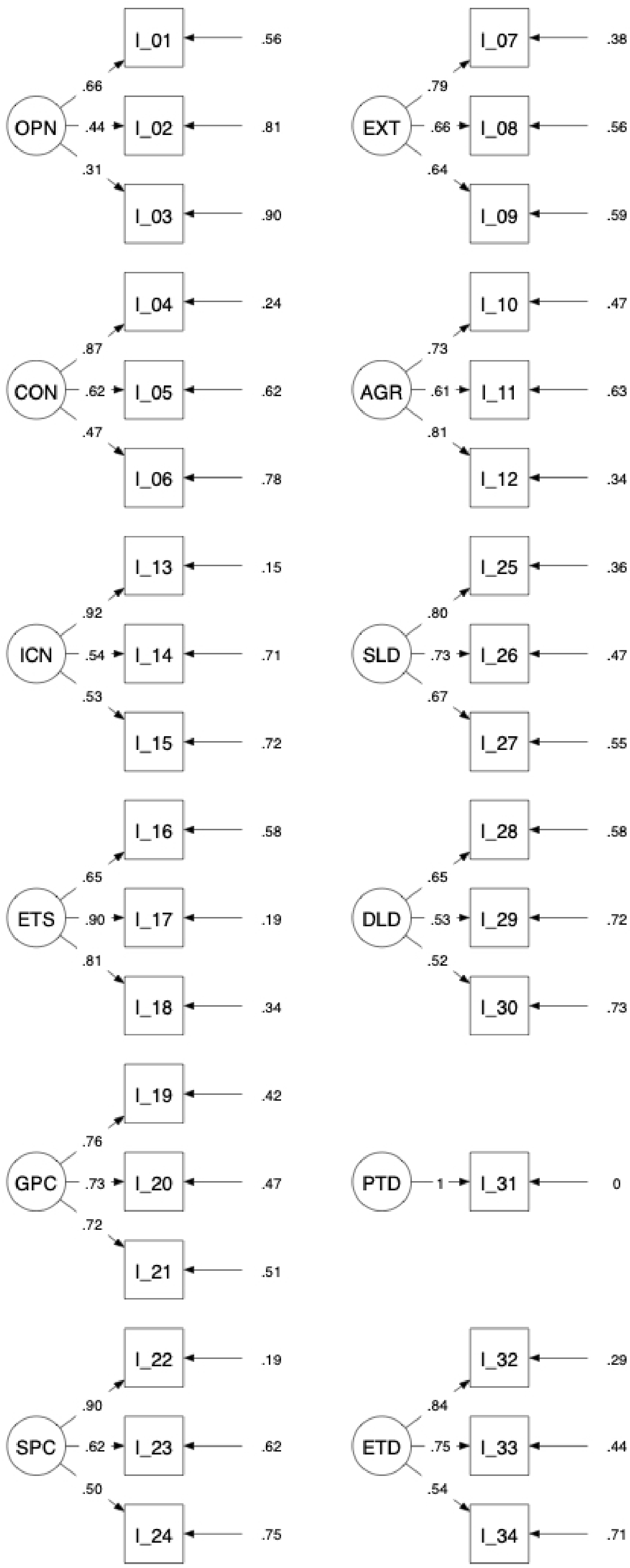

Fig. 1. Measurement models of the SEED instrument

IV. Conclusion

The content analysis of the self-efficacy for engineering design (SEED) resulted in retaining items that experts in engineering design. We showed that the items of the instrument are valid to measure undergraduate students' self-efficacy in (a) design competencies, and (b) personal competencies. The SEED instrument is composed of two dimensions (a) self-efficacy for design competencies (SEDC), and (b) self-efficacy for personal competencies (SEPC).

The conceptualization of engineering design as consisting of these two dimensions is aligned with current thinking in industrial design as well as instruction in engineering education, which takes into consideration the human aspects of design and how essential they should be considered for design practice and education. Because the SEED instrument included only the items that the experts agreed 100% on inclusion, the instrument exhibits high content validity for both SEDC and SEPC.

Regarding the self-efficacy for the design competencies (SEDC), the SEED instrument measures the self-efficacy for eight components of design that are widely accepted in the engineering design literature. Self-efficacy for concept development is a major component of the SEED instrument, because the SEED instrument considers concept development as a critical phase influencing the success of the final product [7] in product development, and according to Ullman [9], this phase is also considered the phase in which almost 70% of the product performance is determined.

Regarding the self-efficacy for the personal competencies (SEPC), the SEED instrument measures the self-efficacy for four components of personality that are widely accepted in the personality and social psychology. The items represent intrapersonal competencies (openness and conscientiousness) and interpersonal competencies (extraversion and agreeableness). None of the initially proposed SEPC items were rejected by the reviewers. Openness represented imagination, acceptance of ideas, and seeking different viewpoints. Conscientiousness represented accuracy, diligence, and achieving high quality work through items about following a plan accurately, assessing the quality of work according to preset criteria, and accomplishing high-quality work before deadlines. Extraversion included communicating product details to customers and engineers, presenting the benefits of a product, and explaining the functions of a product to engineers. Agreeableness included working effectively in teams, sharing responsibility for collaborative work, and valuing individual contributions made by team members.

Limitation of the current work includes the fact that the validation of the SEED instrument was based on a sample of undergraduate students from one educational institution. Hence, the validation of the instrument needs to be tested in other academic populations. Future research can also examine as predictive, convergent, or divergent validities of the instrument.

Engineering design instructors and researchers can administer the instrument to students in engineering design classes and calculate a score for each subscale of the instrument by averaging the scores of the items in each subscale.

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