World Transactions on Engineering and Technology Education
Vol.16, No.2, 2018

Engineering thinking to enhance architectural design

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ABSTRACT: The creative aspect of architecture remains a contentious issue in terms of teaching and assessing at tertiary level where creativity appears as an essential component of the design process. Where and how it fits into the overall structure is contentious. This article introduces a new perspective and direction for assessing and encouraging creativity in the design of applications in architectural design education. Assessment is grounded on engineering thinking developed using design-based activities. To evaluate engineering design, a model, which consists of five sub-factors is proposed and allows measuring divergent thinking, convergent thinking, constraint satisfaction, problem identification, and problem solving. For the purpose of this study, 129 architecture students from Cracow University of Technology were recruited. The research instrument in this study proved reliable and valid. In this article, an argument is developed that identifying students' creative engineering design ability is an alternative to expertise, allowing teaching, learning and assessment to focus on process and product, especially in an architectural design context.

INTRODUCTION

Climate change increases the risk of extreme weather events, including hurricanes, floods and earthquakes. This has led to a professional rethink about the way architects and engineers work together. Several modelling tools and information/communication technology enable a multidisciplinary approach to increasing building efficacy [1], to improve interaction between the natural and social environment [2], and to predict the consequences of decisions in different environments [3].

Architects and engineers have different design foci and methods. Architects are responsible for a design that meets a client's expectations, perhaps given the constraints of a complex site. They must satisfy both functional and aesthetic expectations. By contrast, engineers are more narrowly focused and prefer a linear design approach in their quest for safe, economical and code-complying structures [4][5]. Many architects aspire to create a sense of lightness of building elements, whereas engineers typically focus on grounding, providing force paths from superstructure to foundations.

To satisfy diverse design objectives, collaboration between architects and engineers requires considerable skill, commitment and creativity. Improved designs, construction systems and approaches challenge professionals to understand and embrace other points of view and push the boundaries of their own fields. When it comes to architecture, the evaluation will always include an element that is non-quantifiable. One can handle this problem in the case of the implemented architectural designs; whose evaluation is objectified by the opinion-making criticism [6]. Several authors [4][7-9] suggest a multidisciplinary approach to assessing architectural design, especially in analysing creative behaviour throughout the design process [10].

An architectural design programme is not a simulation or an exercise in individual expression. In a design *studio*, ideas are developed and then documented in material form i.e. word, text, image and model. The knowledge is not so much discovered as it is created and substantiated [9]. A design studio seeks to create an environment in which students work on individual design projects, while tutors move from student to student, offering formative feedback on the projects and reviewing the work in progress as illustrated by a set of architectural drawings and models [7]. Reviewing students' outcomes, three unifying factors are manifest viz:

1) individual aptitude influenced by experience and education;
2) creative processes;
3) creative products.

In the architectural design process the interaction between these factors should be considered an act of creativity [11]. Regarding cognitive factors, much of the research has focused on the relationship of creativity to divergent thinking and intelligence, while cognitive psychologists consider fluency and novelty as the primary measures of ability to generate ideas. However, this is not adequate for engineering design. An engineering design must not only be novel (unusual, unexpected), but it must also satisfy some intended function(s) by meeting required specifications (have desired utility). Thus, engineering designs must be evaluated by metrics somewhat different from those for non-utilitarian artefacts. Engineering designs do not happen by accident; they must satisfy a pre-defined set of specifications, even if these specifications sometimes are modified as the designer and client both get a better understanding of the design problem and design space [8]. Creativity is crucial for designing products and enabling innovation. Assessing creativity can help identify innovative designers and products, and support the improvement of both [5].

Work investigating solution-driven design as a predictor of creative outcomes demonstrates a relationship between student design cognition types and creative design outcomes [12]. Design characteristics, design elements affective characteristics were found as a basis for creative design assessment [4][11]. Therefore, the design *thinking* process to solve complex multidisciplinary problems should be taught as a form of solution-based experimental thinking [13].

ENGINEERING THINKING AND ARCHITECTURE EDUCATION

Engineering thinking focuses on finding optimal solutions to problems [4][14]. The solution criteria may be of several different types, as there is no formal way to find the best trade-off. The thinking, which identifies a particular solution as optimal relies on deduction and analogy. Engineering thinking differs for simple versus compound problems. In simple problems, the constraints and criteria for evaluating the solution are all qualitatively similar. In compound problems, the evaluation criteria are not qualitatively similar and cannot be jointly optimised.

Engineering tasks, which require the balancing of cost, safety and aesthetics are compound problems. Most systems engineering tasks are compound. Wherever there are choices of materials, subsystems, or methods that emphasise one or other property, the problem is compound. According to Robinson, the engineer can now apply several strategies [14]:

- disqualify criteria that cannot be measured;
- express the relative value of criteria in a common *currency* and thus reduce the problem to a simple one;
- divide the problem into parts which can be independently solved as simple problems [14].

The ability to see analogous situations, particularly in balancing the values of different criteria, is central to engineering judgment. In contrast to other disciplines, the very essence of architectural education is project or problem-based learning. It does not seek a single correct answer, but instead encourages students to make speculative and exploratory propositions that reflect their competence and knowledge [15][16].

Architecture is an art and an ability to shape spaces for human needs where the design is the basis of the practice. Students should feel a certain degree of freedom, but ought to be directed, supported and not suppressed [16]. Design is regarded as the peak creative activity; its results are often the absence of some effect rather than the presence of some observable feature [4]. According to Charyton et al, design is creative, consumes resources (information, material, energy), has a purpose, and therefore, can be assessed and evaluated [4] (see Figure 1). Development of creativity and communication skills has been promoted through design-build projects and studio practice [16].

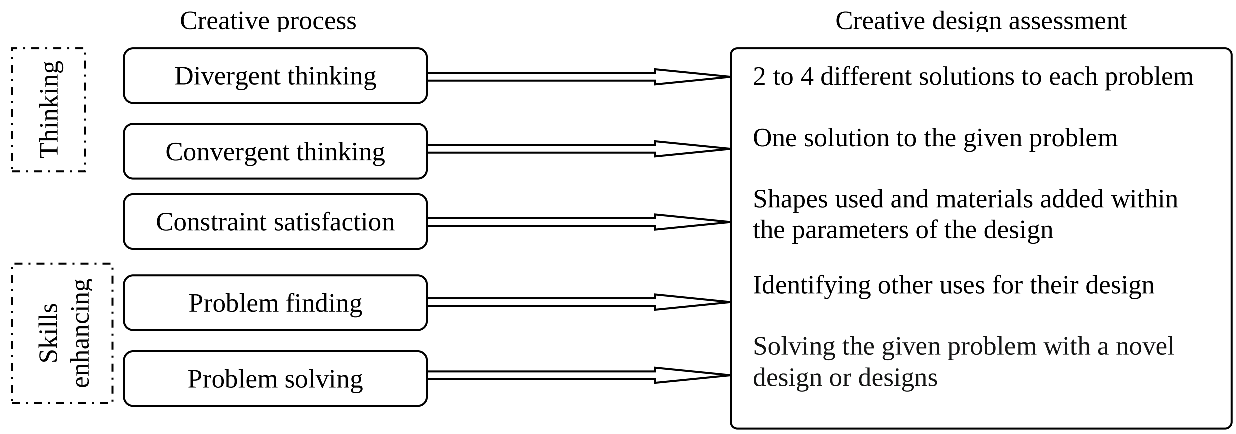

Figure 1: Meta-cognitive processes in creative design assessment.

When designing, uncertainty theory implies a design should have the following characteristics [17]:

- design problems are always subject to conditions;
- conditions serve as benchmarks for judging a solution;
- a design problem is very often a decision-making problem;
- information management is crucial to reach a satisfactory solution;

- a design problem is a real-world problem. The solution will be physical;
- design problems do not have a single solution;
- design theories have a high degree of abstraction and the best solution is as an ideal design, which is achieved by systematically applying advance design theories [17].

Engineering problem-finding skills seem to be more important than problem-solving skills [13]. Considering the above, the effectiveness of architecture education might be enhanced by an emphasis on creativity, multiple learning and visualisation abilities [18].

Architecture Education at Cracow University of Technology

The architecture education curriculum is constructed such as to ensure graduates have the necessary design knowledge and skills. First-year students of architecture programmes at Cracow University of Technology and elsewhere arrive with a diverse range of skills and knowledge as there are no prerequisite high-school subjects. Although knowledge of art and of technical drawing are considered desirable, they are not required. Students typically are split fairly evenly between those with both, one or neither of these backgrounds. While the first-year curriculum has a substantial focus on drawing skills, it also seeks to develop an understanding of the processes of architectural design.

Unfortunately, the nature of the design project as a learning activity and assessment task has long favoured students with an ability to communicate well, visually, through drawing. This often makes it difficult for students with no background in drawing to communicate what may be a well-developed understanding of architectural design. Study of architecture in the first Bologna cycle (undergraduate) includes several elements of engineering subject matter, e.g. physics of structures, mechanics of structures, descriptive geometry, general construction, material science and building installations. At Cracow University of Technology, the first cycle (undergraduate) study lasts three and a half years, while the second cycle (Masters) lasts one and a half years.

The Master of Architecture programme of studies focuses on a wide range of issues directly affecting contemporary architecture and urban design:

- Architectural and urban design in the fields of multifamily housing and public use buildings.
- Spatial and regional planning.
- Preservation of monuments and revalorisation of urban complexes with design for conservation.
- Landscape architecture, architecture and planning in the countryside.
- Building construction systems and building structures.
- Theory of architecture and urban design, as well as spatial and regional planning.
- History of art, culture and contemporary urban design.
- Ecology and environmental protection. Design, history, theory and building structure technology are taught to prepare students for professional registration as architects in the European Union.

In the second cycle (Masters), a main focus is on creativity and less on engineering. Creativity in architecture has no universal or authoritative definition. A dilemma can occur in assessing a student’s work, because of a difficulty in defining creative design. Both students and faculty agree on levels of creativity when they *see it*, regardless of a set definition and without stated opinions during the design and critiquing process. Students were asked to apply a number of architectural design concepts to a simple one-day design problem [19]. They then comparatively analysed and critiqued the projects in group discussion moderated by the faculty [20]. Sometimes evaluation of the design works is attended by external examiners who are not employees of the Faculty of Architecture, i.e. members of the Lesser Poland (regional) Chamber of Architects. The participation of such external examiners in the evaluation of design works is agreed by the subject supervisor and the Chamber, then communicated to students during the first class in the semester.

Since engineering thinking in design is close to creativity, it is of interest to find how engineering design ability develops during architecture education. In this work it was hypothesised that architecture creativity would overlap with engineering design creativity. This could be assessed using a questionnaire as a research instrument. This research questions included:

- What is the level of a creative engineering design in freshman and senior students?
- What are the similarities and differences between male and female architecture students in terms of creative engineering design?
- Does creative engineering design have a predictive value for self-reported grade point averages?

METHOD

Sample

The sample for this study consisted of freshman students (first year) and their senior counterparts (fifth year) enrolled in architecture at the Cracow University of Technology. A questionnaire was distributed to the students. Of the 150 enrolled students, 129 completed the survey entirely (21 had missing values). There were more female respondents (70.5% of 129) than males (29.5% of 129). More than half of the respondents took undergraduate-level courses. Freshmen were 62.8% of the 129, while senior students were 37.2%.

Research Instruments

A questionnaire was administered requesting information including age, gender, faculty major, year of study and grade point average (GPA). To assess creativity specific to engineering design a modified test for creative design assessment was used [4]. The instrument consisted of three design problems with five parts each to assess an individual's ability to formulate and express design ideas through sketching, providing descriptions and identifying materials, as well as identifying problems that the design solves and its potential users. Participants were to generate up to two designs per problem. Total time for this assessment was 30 minutes for three problems or about 10 minutes per problem. Dimensions of assessment included both problem solving and problem identification. Problem solving is the ability to derive a solution to a problem or situation. Problem identification is a skill, often found in art, yet also necessary in science and engineering. Problem identification is the ability to identify a problem or be able to foresee potential problems that may occur, but have not yet occurred. Constraint satisfaction was also assessed, where students used shapes and materials within the parameters of the design. Moreover, both convergent thinking, where students provide one solution to the given problem, and divergent thinking, where students provide two to four different solutions to each problem, were also measured by this instrument. Problem identification, problem solving, constraint satisfaction, divergent and convergent thinking are all relevant to an engineer's creativity [4].

Participants were ranked from 0 to 10 for each design problem based upon:

- Fluency: amount of ideas; number of ideas.
- Flexibility: differing types of idea, categories of idea, number of different kinds of idea.
- Originality: new ideas.

Participants were also ranked from 0 to 4 for each design problem based upon *usefulness*, which is defined as the practicality of a design based on reliability, number of purposes and number of applications both present and new.

Procedure and Data Analysis

Students participated in the study during real-world classroom sessions throughout a study day. Administration of the survey was performed in June and September 2017. A high response rate was obtained because of the presence of teachers and instructors.

Data analysis was conducted using SPSS software. Descriptive analyses were conducted to present the student basic information, and the mean scores of dependent variables. An ANOVA (analysis of variance) and MANOVA (multivariate analysis of variance) analysis were conducted to find and confirm significant relationships between groups with an effect size calculated using Eta squared (η^2).

RESULTS

Reliability

The Cronbach's coefficient alpha values, based on the sample of this study, indicated that the instrument is highly reliable (Table 1), with all Cronbach's alpha values being > 0.60.

Table 1: Reliability information Cronbach's alpha on creative design - total and subscales.

(Sub)scale	Creative engineering design (total)	Fluency	Flexibility	Originality	Usefulness
Cronbach's α	0.88	0.90	0.91	0.84	0.81

Creative Design Assessment

The Levene's test confirmed that the study sample did not violate the assumption that the sample is normally distributed with F (1,127) = 0.45, with a significance level $p = 0.51 > 0.05$. Freshman students had a mean, $M = 74.28$, with standard deviation SD = 24.92, while their senior counterparts scored higher with $M = 95.25$ and SD = 25.58. An ANOVA test of between-subjects effects revealed that senior students scored significantly higher ($p < 0.001$) with a strong size effect $\eta^2 = 0.141$. An in-depth analysis across the test subscales is provided in Figure 2.

The null hypothesis was that the error variance of the dependent variable was equal across groups for the creative design subscales ($p > 0.05$). MANOVA tests of between-subjects effects revealed significant differences ($p < 0.001$) with strong effects for architecture education only for subscale *fluency* ($\eta^2 = 0.22$) and *flexibility* ($\eta^2 = 0.20$). Subscales of *originality* and *usefulness* of creative design were not significant ($p > 0.05$).

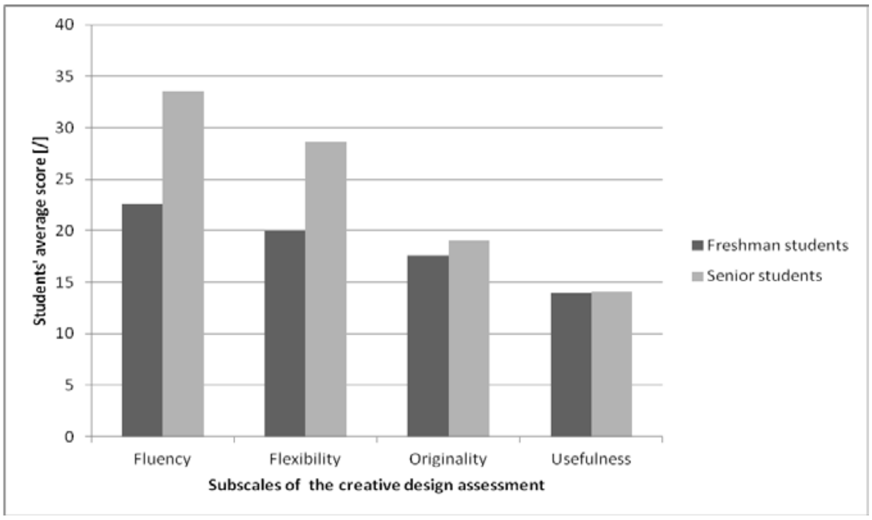

Figure 2: Evaluation of students' creative design.

Since engineering design is about both creation and design, many believe that spatial reasoning and visualisation ability contribute to success in engineering design [21-23]. Thus, it is interesting to investigate gender effects. The test of between-subjects effects revealed significant differences for *fluency* and *flexibility* in favour of males (Figure 3). Effect size was small ($\eta^2 = 0.02$).

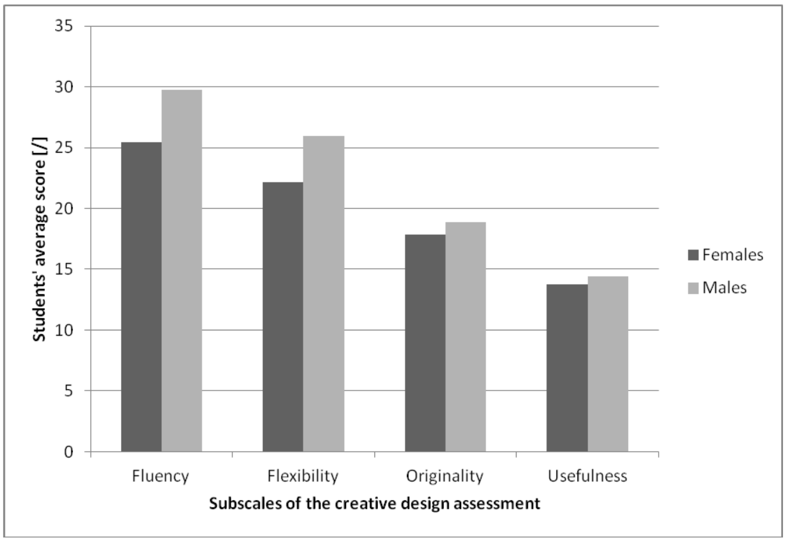

Figure 3: Evaluation of students' creative design by gender.

There were no gender differences on the creative design assessment for the total score ($p = 0.062 > 0.05$). Similarities were also found in visual spatial skills between male and female students. There were no significant gender differences in spatial visualisation, unlike past studies indicating that males tended to perform better than females [4].

A multiple regression analysis was carried out, with the items of students' creative design as independent variables, and GPA as the dependent variable. The authors assumed a linear relation between independent (predictor) and dependent (criterion) variables, meaning that increases or decreases in one variable would be related to increases or decreases in another. It was found that only scores on subscale *originality* significantly predict GPA with a beta (β) weight of 0.32.

It can be understood that the higher the ability to create original/innovative products, the higher the GPA. Moreover, the results indicated that as the degree of complexity of a project increases, a designer's experience may boost the effect of cognitive ability in the design process. Thus, these results confirmed the findings of Nazidizajin et al [24]. The other three categories - *fluency, flexibility* and *usefulness,* do not significantly predict GPA.

CONCLUSIONS

Demonstrated in this article is how creative engineering design assessment can accommodate a group of architecture students with a diverse range of prior knowledge, skills and experiences. Also shown is how design assessment can be used to map the activities and tasks against the design framework, and thereby, develop a more complete and holistic assessment pattern. Activities that foster creativity should be a component of the curriculum, so that students can practice and develop these skills. Architectural design project learning activities offer a good environment for learning, all of the activities of design-based learning.

The findings suggest both female and male architecture students have similar spatial skill abilities. The authors speculate that female architecture students perform as well as male architecture students, because women have more access to educational resources and are more persistent in study. More research is needed addressing spatial performance across genders. Both male and female architecture students were successful in designing a functional artefact. The findings also suggest that these functional design skills may differ from creative design skills.

The creative design assessment reported here could complement educational programmes since the tool measures *originality* and *usefulness* that are core components of creativity. The instrument can provide valuable information on assessing the usefulness of designs. Using a method for assessing creativity in design activity, educators can enable students to develop their talents as future innovative architects. Future studies will be focused on how design cognition types might predict creative outcomes in actual design tasks.

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