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# Creativity and critical thinking in engineering design: the role of interdisciplinary augmentation

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ABSTRACT: Generating and transforming representations in design ideation plays a central role in the designer's process. Several interactions and experiences gained during design might affect students' critical thinking, its perceived utility, and lead to misconceptions about knowledge conceptualisation. How knowledge transfer interacts with visualisation in engineering design remains unanswered. To address this question, a sample of 170 students from different disciplines at the University of Ljubljana, Ljubljana, Slovenia, where critical thinking is taught in a different way, was collected. Both ways of thinking in engineering design, critical and creative, were analysed. The findings show that synergy of creativity and critical thinking is enhanced in design ideation by connecting interdisciplinary augmentation with teacher education. Pedagogical content knowledge of pre-service technology and engineering teachers was found to be central to critical thinking, while visualisation ability using the active learning environment might overcome learning misconceptions and improve innovation learning.

Keywords: Engineering design, critical thinking, creativity, synergy, interdisciplinary augmentation

## INTRODUCTION

Market competition dictates new needs and improved ability to survive in a highly technological knowledge-based society. Seemingly, an ability to innovate was found to be a key competence or skill for sustainability and success for individuals and organisations [1][2]. Engineers and educators will need to work more towards innovative workplace behaviour to develop innovations in companies, research and development institutions and in education. To fill this void, both engineers and organisations in highly competitive markets have to behave in an innovative manner for the sake of survival. Innovative behaviour of engineers is important for keeping up-to-date with the rapidly changing social and natural environments, while upcoming new technologies and new insights about teaching require innovative behaviour.

Education is crucial to promoting engineering students' creative and innovative thinking. Indeed, the worldwide demand for engineers has been increasing rapidly; however, many engineering students have not yet achieved the ability to creatively problem-solve in rapidly diversifying and innovative fields. Therefore, engineering curricula need to foster students' abilities to solve problems and view projects from an interdisciplinary perspective that leads to innovation within design as a central element of engineering [3].

Engineering design combines creativity with innovative engineering techniques by converting new ideas into tangible forms, where scientific knowledge is applied to solve problems of interest to society. It has been recognised as an effective approach to engage students in science, technology, engineering and mathematics [4]. An ultimate goal of engineering design is to enable the sustainable realisation of a product [5]. Thereafter, a design is viewed as a context for thinking, doing and learning. The visual representation of a product and the role of visualisation have recently become a central issue in design research, because much of design is concerned with concrete qualities of the design elements to be designed, and effective ways of achieving plausible solutions, while the design thinking pathway considers aspects of desirability, viability and feasibility of potential products [6].

Moreover, a visual representation in design is viewed as a transaction between conceptual knowledge and visual knowledge, which enables the designer to act proactively as the design progresses [7][8]. It seems that visual ability is connected with metacognitive skills, which enhance a student's ability in predictive analysis and model testing/revising [4] as the core elements of design thinking. Different design techniques might enhance creative thinking and improve communication skills as higher order thinking skills also use critical thinking during problem-solving [9].

Critical thinking and higher order thinking skills are often associated with creativity and/or creative thinking [5]. Critical thinking ability requires the possession of a sufficient knowledge base within a specific subject area to be demonstrated [10], and is one of several generic attributes that are conceptualised and taught in different ways [11]. Subject matter knowledge of students within different disciplines might not be enough to develop critical thinking skills, but these skills are needed for conceptualisation inside a specific subject area. Task variation and mental model divergence may influence the transfer of team learning, especially in design [12]. A catalyst of this knowledge transfer seems to be pedagogical content knowledge (PCK) [6][7][11]. It was also argued by Rohaan et al that a sufficient level of PCK might improve higher order thinking outcomes in engineering and technology education, where PCK is a transformation of different knowledge domains into a new and unique domain [13]. Pedagogical content knowledge is conceptualised as [2][13]:

- knowledge of students' concept of engineering and technology, and knowledge of their pre- and misconceptions related to engineering and technology;
- knowledge of the nature and purpose of engineering and technology education;
- knowledge of pedagogical approaches and teaching strategies for engineering and technology education.

In this article, the effects of these interactions are contemplated by solving engineering design problems within the technical disciplines, where designs of sound generation, communication facilitation and transportation solutions are presented to the students from different majors. These students have non-symmetrically developed design ability, visualisation and representations ability from a different PCK (Figure 1).

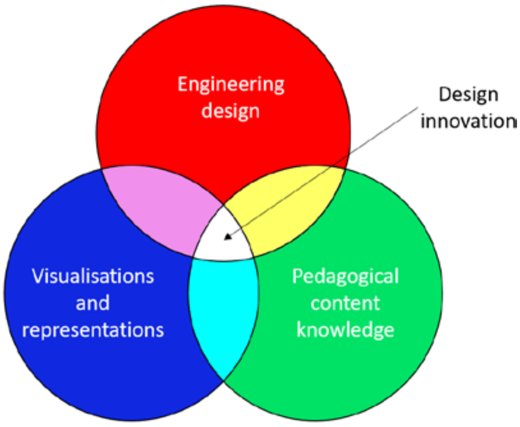


Figure 1: Conceptual framework of the study.

The authors aimed to explore how creative problem-solving of students from different disciplines does make synergy with their critical thinking ability and how the discipline's specifics do create an augmentation needed for design innovation. It was intended to use cases where rigid engineering rational decisions based on constraints are necessary conditions, despite the fact these cases where many shades of decision-making inevitably are unclear.

## CREATIVITY AND CRITICAL THINKING FOR DESIGN INNOVATION

Creativity and design leading to innovation also has been recently promoted as the key to global economic competitiveness [2]. Creativity is the ability to produce ideas, processes or products that are novel; original, unexpected, imaginative and useful; as well as appropriate or adaptive regarding task constraints [14]. Creativity plays a significant role in problem-solving activities in comparing, evaluating and assessing, choosing, combining, and using knowledge and skills in relation to usability, to reach a practical solution [2]. Amabile offers a definition of creativity that is relevant for engineering and technology education:

> *A product or a response will be judged as creative to the extent that (a) it is both a novel and appropriate, useful, correct or valuable response to the task at hand, and (b) the task is heuristic rather than algorithmic* [15].

Esjeholm reported four criteria for identifying creativity in the domain of design that may be seen as a further specification of Amabile's definition [16]:

- Conceptual creativity - the concept or idea: has the designer proposed a concept that is original, novel, feasible, useful, will function, and so on?
- Aesthetic creativity: has the designer made proposals about those features of the product that will appeal to the senses, for example sight, hearing, touch, taste and smell?
- Technical creativity: has the designer made proposals about the way the product will work and the nature of the components and materials required to achieve this?
- Constructional creativity: has the designer made proposals about the way the product will be constructed and the tools and the processes needed to achieve this?

Creativity traditionally is regarded an intrinsic trait of humans. Also Atkinson [17] argues in favour of creativity as a skill that can be taught through working with problem-solving strategies and that engineering design has an unleashed potential of stimulating students' higher order thinking where critical thinking has a central role in learning [10]. Moreover, developing critical thinking skills also can enhance the ability to draw sound conclusions and make informed decisions [10], especially useful in engineering design [5].

Design entails not only creative ability, but analytical and practical skills as well. Design education requires a meta-cognitive approach to develop creative processes that can be made tangible for designers to reflect on prior experiences and knowledge, thus giving the designer an ability to solve any particular design challenge [5][9][18].

Halpern provides a definition of critical thinking as:

> *Critical thinking is the use of those cognitive skills or strategies that increase the probability of a desirable outcome. It is used to describe thinking that is purposeful, reasoned, and goal directed - the kind of thinking involved in solving problems, formulating inferences, calculating likelihoods, and making decisions, when the thinker is using skills that are thoughtful and effective for the particular context and type of thinking task* [11].

Critical thinking is more than merely thinking about one's own thinking or making judgments and solving problems; it is effortful and consciously controlled. Critical thinking uses evidence and reasons, and strives to overcome individual biases. In this process of evaluation, one's attitude, knowledge and thinking skills are involved [11]. Decisions as to which outcomes should be desirable are embedded in a system of values and may differ from person to person [4][11]. Higher cognitive accomplishments require that an individual uses many kinds of external representations as sources of knowledge, organisers of activity, and in general extensions of one's cognition.

Through visualisation, advantages of the powerful human visual system can be used to facilitate problem-solving of design issues, where visual representations play varied roles as thinking drawings (presenting a conceptual or visual idea), prescriptive (modifications of the basic ideas) and talking drawings (the ideas are constantly drawn in discussion with others). In this process of mentally constructing, shaping and understanding information [19], an ability to externally communicate information may be developed as a pathway for design [9][19] and innovation learning [2], where one negotiates between drawing and making to formulate, verify and modify representations of thought [9][20].

In the design process, there is an intimate relation between production of drawings and prototype or model-making. A contemporary information communication technology provides powerful tools for 3D modelling, where a model or prototype creation and optimisation are made first, afterwards final drawings for technical manufacturing are produced. Further, algorithmic and parametric design allows the designer to modify and correct a structure at any stage of creation [21], while use of direct manipulation environments may scaffold learning and creativity to overcome misconceptions in learning [22]. Visual literacy is a critical skill for thinking, understanding, exploring and communicating physical concepts, as argued by Anderson and Lilly [19].

## METHODOLOGY

### Sample

The sample comprised 170 undergraduate students from different higher education disciplines from the University of Ljubljana, Slovenia. They were pre-service technology and engineering teachers (N = 61), students of chemistry (N = 49) and engineering students from different majors (N = 60). They were aged between 20 and 23 years, and there were 128 females (75.3%) and 42 males (24.7%).

### Research Instruments

To assess creativity specific to engineering design, a modified test for creative design assessment (CEDA) was used [23]. 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 [23].

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

- Fluency: number of ideas,
- Flexibility: differing categories of ideas,
- 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.

The Cronbach's alpha, based on the sample of this study, indicated that the instrument is highly reliable, at 0.91.

The critical thinking 27-item questionnaire was used to assess students' [10]:

- *Confidence in critical thinking:* 17 items related to self-efficacy and confidence, as well as self-reported critical thinking behaviour;
- *Valuing critical thinking:* six items related to the perceived utility of critical thinking for good performance in higher education;
- *Misconceptions:* four items related to misconceptions about higher education, critical thinking and conceptual knowledge.

For assessment, a 10-point Likert scale was used, from 10: strongly agree, to 1 strongly disagree.

Internal consistency was analysed using Cronbach's alpha. The items in *Confidence in critical thinking* and *Valuing critical thinking* demonstrated high reliability (Cronbach's $\alpha$ = 0.90 and 0.86, respectively). The sub-scale of *Misconceptions* items demonstrated moderate reliability (Cronbach's $\alpha = 0.74$).

Procedure and Data Analysis

A paper and pencil method was adopted by instructors to distribute the questionnaire and the test. Students participated in the study during real-world classroom sessions throughout a study day, and they were briefed about the study and ethical considerations, before completing the questionnaire and validation tasks in classrooms. Administration of the CEDA test and the critical thinking questionnaire were performed in October and November 2018. Participants first completed the critical thinking questionnaire, and they then completed the CEDA test. There were no time limits imposed on participants at the critical thinking questionnaire, while the CEDA test was limited to 30 minutes. A high response rate was obtained, because of the direct presence of teachers or instructors and testing administration.

Data analysis was conducted using SPSS software. Descriptive analyses were conducted to present the student's basic information and the mean score of dependent variables. An ANOVA and multiple regression analysis were conducted to find and confirm significant relationships between groups with an effect size calculated using eta squared ($\eta^2$).

RESULTS AND DISCUSSION

One-hundred and seventy higher education students from three different disciplines were involved in this study. There were more female students than males, while students' distribution across the disciplines was balanced. Test of equality of variances revealed no significant differences across groups in analysis.

A comparison regarding the sex of students revealed that female students scored higher than males in *Confidence in critical thinking*, *Valuing critical thinking* and in *Misconceptions* ($Mean_f$ = 7.31, $M_m$ = 7.01, $M_f$ = 7.48, $M_m$ = 6.33; $M_f$ = 6.41, $M_m$ = 6.36, respectively). A significant difference appeared only at a sub-scale of *Valuing critical thinking* with a medium effect size of $\eta^2 = 0.09$. This sub-scale is of special importance, because it might predict the students' grade point average in addition to that predicted by the aptitude-based measures which was argued by Stupple et al [10].

The critical thinking questionnaire measured students' beliefs and attitudes about critical thinking on three sub-scales and revealed that student experiences differed between study disciplines (see Figure 2). Test of between subjects' effects revealed significant differences ($p < 0.05$) in all three sub-scales. In the *Confidence in critical thinking* sub-scale, significant differences were found for engineering students, with a moderate effect size $\eta^2 = 0.11$.

The *Valuing critical thinking* is most developed in pre-service technology and engineering teachers against other counterparts, with strong effect size $\eta^2 = 0.15$ (against engineering students) and medium effect size $\eta^2 = 0.06$ (against chemistry students). On a sub-scale of *Misconceptions*, a significant difference appears only between chemistry students and engineering students, with a small-to-medium effect size $\eta^2 = 0.05$. It points to engineering design thinking being thought of as a form of solution-based experimental thinking [20].

Students from different disciplines have different knowledge, skills and attitudes towards technology and engineering, which brings a new quality to design ideation. Creativity in students has been developed in a different way, where physical and sensory aspects of making, processing, use of tools, machines and devices result in generating and transforming representations in idea generation in the design process.

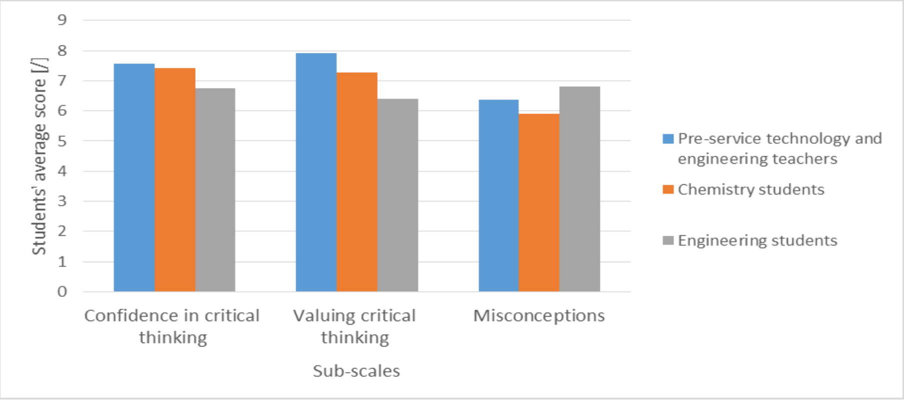


Figure 2: Students' performance in the critical thinking questionnaire across study disciplines.

Since engineering design is about both creation and design, many believe that spatial reasoning and visualisation ability contribute to success in engineering design [8][19][24]. Figure 3 shows how successful students were in design tasks, measured with CEDA on four sub-scales. In the total score, pre-service technology and engineering teachers, chemistry students and engineering students differ significantly ($p < 0.05$) in a mean expressed in number of points collected on the CEDA test ($M = 96.44$, $M = 94.04$, $M = 86.16$, respectively), where an effect size was small $\eta^2 = 0.03$.

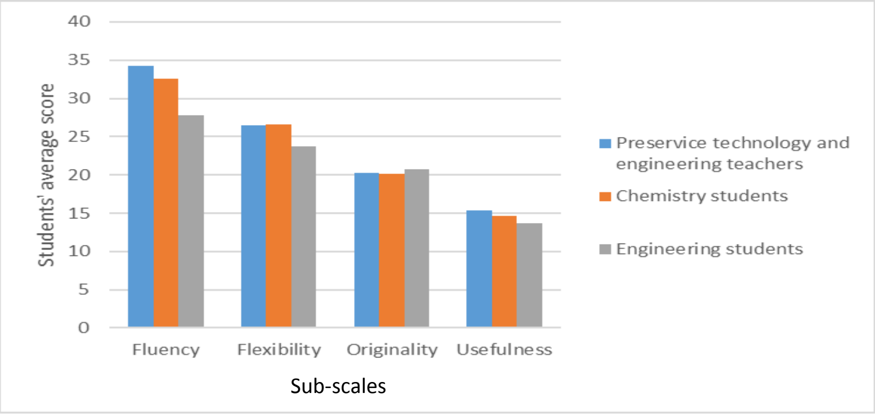


Figure 3: Evaluation of students' creative design.

Figure 3 shows that pre-service teachers scored significantly higher in comparison with engineering students, with the effect size medium $\eta^2 = 0.07$. Sub-scales of *Flexibility* and *Originality* of ideation were not significant ($p > 0.05$) across the disciplines, while at scale of *Usefulness*, a significant and moderate effect was found ($\eta^2 = 0.06$) in favour of pre-service technology and engineering teachers against engineering students.

At ideation, a gender effect was found. Females scored significantly higher than males ($M = 98.05$, $M = 74.05$, respectively), with the strong effect size $\eta^2 = 0.17$. Further investigation revealed that females scored higher at *Fluency*, *Flexibility*, *Usefulness* ($M_f = 34.32$, $M_m = 22.91$, $M_f = 27.41$, $M_m = 19.95$, $M_f = 15.27$, $M_m = 12.61$, respectively) with the strong effect size ($\eta^2 = 0.19, 0.14, 0.15$, respectively). *Originality* of design ideas was comparable in females and males, with the small effect size ($\eta^2 = 0.04$) in favour of females. It seems that female students were more divergent thinkers, where learning interventions were focused on active and open learning in a form of confidence-building activity.

A correlation analysis was performed on whether predictors of CEDA score exist through critical thinking sub-scales. The results of the regression analysis show that both *Valuing critical thinking* and *Misconceptions* significantly predict a CEDA total score. *Valuing of critical thinking* seems to be a strong positive predictor of CEDA score (beta weight $\beta = 0.34$, $p = 0.000$), while a factor of *Misconceptions* was found as a moderate negative predictor of CEDA score ($\beta = -0.17$, $p = 0.032$). The authors' findings seem to be parallel with findings of Stupple et al [10], where they found the same two factors as predictors of critical thinking in explaining variation in grade point average. It seems that some correlation could exist between CEDA scores and students' grade point average.

## CONCLUSIONS

Design as a central activity in engineering can be performed with extensive use of digital technology, which enhances interaction in both real and virtual environments also using a different data basis and e-clouds. Moreover, educational technology allows and stimulates interactions with other disciplines to enrich design and idea generation, especially when the synthesis is made with design and engineering in higher education of transfer abilities, visualisation and representations capability.

The methods and forms used in chemistry education that often involve critical and/or abstract thinking (e.g. planning and optimisation of laboratory experimental work, explanation of the macroscopically observable phenomena on the abstract particle level by the use of models and modelling, notation of the macroscopic observations with symbolic chemical equations) may be useful at overcoming misconceptions, while knowledge transfer ability stimulates and enhances conceptualisation of knowledge, and consequently the developing of critical thinking skills needed for advancement of design and idea generating.

The findings suggest a mapping of students' needs to improve their learning and acquiring creative and critical thinking skills to facilitate students' development as critical and innovative designers. Further research is needed to expand this methodology to other disciplines, such as fine arts, architecture and industrial mechanical engineering, to identify a wider range of critical thinking resources needed for the ideation process.

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BIOGRAPHIES

Stanislav Avsec received a BSc degree in mechanical engineering, an MSc degree in economics and a PhD degree in technology education, all from the University of Ljubljana (UL), Slovenia. He works as an associate professor of teaching and learning strategies in technology and engineering education in the Faculty of Education at the University of Ljubljana. He is the Head of Department of Physics and Technology Education and Head of the Committee for International Cooperation, both at the Faculty of Education, as well as a member of University Senate. He also works as a manager, researcher, teacher and trainer at several EU and nationally funded projects. He is an active researcher in technology and engineering education, educational technology, creativity and inventiveness, and in environmental science and management. He is a member of editorial advisory boards and a reviewer for several journals in the area of technology and engineering education, teaching, learning and individual differences, educational technology, environmental management and engineering.

Vesna Ferk Savec began her work at the University of Ljubljana (UL), Slovenia, in 1998 in the Faculty of Natural Sciences and Engineering, as a teaching assistant. There she also completed her PhD in the area of chemistry education in 2003 and received her assistant professorship in 2007. Since 2014 she has been employed in the Faculty of Education, UL, where she has been involved in pedagogical and research work, and received her full professorship in 2018. She aims to expand her knowledge by conducting research work also in other academic institutions, e.g. the University of Rennes (France, 1997/1998), the University of Reading (UK, 2000/2001) and the University of Helsinki (Finland, 2016), as well as by an involvement in various national and international projects. Her current research interests are focused primarily on the visualisation of the triple nature of chemical concepts and processes, the implementation of green chemistry in school practice and society, educational technology, creativity and the relevancy of schools-university-industry collaboration in the STEM area.