World Transactions on Engineering and Technology Education
Vol.18, No.2, 2020

Investigation into design thinking in mechanical engineering students

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ABSTRACT: An increased interest in design thinking (DT) as an educational approach to innovation in higher education raises several questions. Design thinking is an iterative and non-linear process. How the phases contribute to design performance to overcome cognitive fixation needs deeper insights. The aim of this study was to investigate design thinking in mechanical engineering students involved in engineering design. A sample of 110 undergraduates was chosen and regression analyses were used to find significant relations between variables. Critical thinking, idea generation and creative engineering were analysed to create a model for analysis. Critical thinking was found to be an important positive predictor of both creative ideation and design, while creative ideation significantly predicts the originality and usefulness of transdisciplinary design activities. The results support innovation learning and provide deep insights for teaching and assessment using design thinking.

INTRODUCTION

Science and technology play an increasingly important and transformative role in modern society, especially given increased global networking and interconnectedness. Science and technology hold promise of fundamental changes to human and other systems over ever-shorter time periods, e.g. biotechnology allows the construction of the basic biological building blocks of life. In modern societies, technological innovation is closely linked to economic competitiveness and social development. The trend towards technological transformation is likely to continue [1].

Creativity and innovation are key elements in achieving a higher quality of life with reduced environmental impact and, at the same time, addressing major societal challenges, such as public health, an aging population and climate change [2]. Creativity and innovation promotes higher productivity, better services and greater prosperity. It facilitates new business models that offer greater flexibility to both employers and employees [1].

To meet the requirements of companies for well-trained employees, a significant change in the system of education is needed. This requires new learning approaches, strategies and methods, nationally and internationally, across all disciplines [2]. A transdisciplinary educational approach to innovation has several benefits, such as increased quality of products and goods, cost reduction and production flexibility [2]. The education may involve design thinking, where students experience transdisciplinary teamwork involving community stakeholders [2][3].

User experience (UX) design involves a shift towards interactive design, involving stakeholders in a natural, economic or social environment [4]. The UX design process takes into account interactive user experience [4] of a service or product [5]. Rather than focusing on the design per se, UX focuses on the user. It can be effective for complex projects, start-ups and long projects. User experience design is a user-centric, integrative process with multiple feedback loops to determine user needs, and has four consecutive steps [5]:

1) determine the context of the system;
2) specify the user requirements;
3) design the solution;
4) evaluate the solution against the requirements.

The design thinking method (DT) has been proposed for the design in UX [4-6]. Design thinking consists of five phases, which are not always sequential and do not follow a particular order:

1) empathise;
2) define;

3) ideate;
4) prototype;
5) test [5][6].

Design thinking has gained in importance because of its use in many disciplines, both in engineering and in other fields. However, there is a need for more insight into the nature of the process itself. How can creativity using DT be encouraged, especially in higher education?

THEORETICAL BACKGROUND

Design thinking employing UX design has seven key factors against which it should be evaluated [5-7]. These seven factors are identified as:

1) useful;
2) usable;
3) discoverable;
4) credible;
5) desirable;
6) accessible;
7) valuable.

Design thinking as a cognitive process is the ability to combine empathy, creativity and rationality to analyse and adapt solutions to specific contexts [2].

An important aspect of DT/UX design is to empathise, in which the designer should think about the *why*, *what* and *how* of product use [8]. Cognitive empathy is concerned with *what* the user does, *what* happens in the background, *how* it is seen and with the functionality and properties of the product or process [5][9]. Emotional contagion deals with the way the user feels and tries to describe the emotional impact of performing a task and reflects functionality in an accessible and aesthetically pleasing way [5][6]. An important aspect of the design is to interpret the scene based on *what* and *how* observations; the designer must intuit the emotional drivers behind the user and find out *what* a user expects. The *why* concerns the motivation, values and attitudes of the users to accept and own the product or process [10].

Another important aspect in DT is creative ideation. How to find new ideas, technical improvements and innovations is a challenge for any designer. Creativity plays an important role in DT as a bridge to research and concept formation [6]. Through several iterations of ideation, prototyping and testing, creativity plays a significant role in problem-solving. It enables comparing, evaluating, choosing, combining, and using knowledge and skills in relation to usability to reach a practical solution [5-7].

A third aspect of DT is rationality, which is manifest throughout. Constraints apply from the empathy phase to final testing of a design. Rationality ensures a balance between what users need, is good for them or can cope with, and can be accomplished within the constraints of time, budget, materials and other resources [4][6]. At any stage, designers or design teams should be informed by different point of views from a number of different areas [11].

Designers should have knowledge and skills from other disciplines outside the design, such as psychology, human behaviour and business development [12]. It entails not only creative ability but analytical and practical skills as well to merge social science with entrepreneurship [12].

Design education requires a metacognitive approach to developing creative processes that can be made tangible for the designers, reflecting previous experience and knowledge, and thus giving the designer the ability to solve a particular design challenge [7][13][14]. During design, designers use different mind tools for creative idea generation, with critical thinking appearing as an important influencing factor [15]. Critical thinking can have both positive and negative influences on creativity. A negative evaluation can have a negative impact on design performance and cause a loss of productivity [15][16]. On the other hand, critical thinking can positively influence the flow and flexibility of ideas and contribute to the originality of the design [15].

Moreover, critical thinking enables convergent thinking and rationality, which can improve the usefulness of designs. This is of considerable importance in engineering design, which represents an intersection of creativity and utility. Engineering depends largely on analytical and critical thinking skills, but these skills grow in complex ways over time. Engineering also depends largely on motivation, which is linked to the assessment of critical thinking [10][17].

The idea-generation methods used in DT support designers in generating alternative designs. This determines qualitative and quantitative characteristics of the designs [10]. It is, therefore, of great importance which mind tools can be used to avoid cognitive fixation in design thinking [18]. Special attention should be paid to the transition from research results to concept development, so as not to lose the reference to user research [5][6]. To avoid a design fixation, critical thinking should be oriented towards a persistent evaluation to determine whether designs are useful and have potential for current or potential users [10].

Design thinking requires empathy, curiosity, imagination and creativity to generate, explore and develop possible solutions [3], and depends on the level of critical thinking skills as a complement to creativity [3].

Against this background, the following research questions were addressed:

- What are mechanical engineering students' perceptions and experiences of critical thinking?
- What is the level of creative ideation in mechanical engineering students?
- What is the creative design ability of mechanical engineering students?
- What is the predictive value of students' critical thinking for their creative ideation and design ability?

METHODOLOGY

A one-group post-test only design was followed in this study. Students in the study worked as product-design teams analysing food-processing techniques and lighting solutions, as well as daily personal mobility for the elderly. After the full cycle of integrated design, students were surveyed on critical thinking and ideational behaviour, and then tested on their engineering design abilities. Several independent variables were studied to find predictors of dependent variables.

Sample

The sample consisted of 110 undergraduate students from the Faculty of Mechanical Engineering at the University of Ljubljana, Slovenia. They were aged between 21 and 23 years. There were 9 females (8.2%) and 101 males (91.8%).

Instruments

To assess creative ideation, students filled out the Runco Ideational Behavior Scale (RIBS) [19] questionnaire, a self-reported inventory that contains 23 items on a five-point Likert scale (1 - never to 5 - very often). This had two subscales:

- General ideational behaviour - 17 items related to problem finding, problem identification and definition, ideation, judgment, evaluation or appraisal.

- Task switch ability - six items related to divergent and convergent thinking, intrinsic and extrinsic motivation.

Cronbach's alpha, based on the sample of this study, indicated that the instrument was highly reliable for general ideational behaviour (Cronbach's $\alpha = 0.86$) and moderately reliable for the task switch ability subscale (Cronbach's $\alpha = 0.78$).

The critical thinking toolkit (CriTT) with three subscales and 27 items was used to assess [17]:

- 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 to aid 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 (10 - strongly agree to 1 - strongly disagree).

Internal consistency was analysed using Cronbach's alpha. The items for confidence in critical thinking demonstrated high reliability (Cronbach's $\alpha = 0.89$), while the items for valuing critical thinking and of misconceptions demonstrated moderate reliability (Cronbach's $\alpha = 0.75$ and 0.71, respectively).

To assess creativity specific to engineering design a modified test for creative design assessment (CEDA) was used [20]. Participants were ranked from 0 to 10 for each design problem based upon originality, and from 0 to 4 for each design problem based upon usefulness [20]. Categories of fluency and flexibility of design concepts were also assessed.

The Cronbach's alpha of 0.85, based on the sample, indicated that the instrument was highly reliable.

Procedure and Data Analysis

Research was performed in the academic year 2018/2019. University professors and their teaching assistants distributed two questionnaires and the test. Students participated in the study during classroom sessions throughout a study day and they were briefed about the research and ethical considerations, before completing the questionnaires. The RIBS was performed, followed by CRiTT, and then the CEDA test. No time limits were imposed on participants for RIBS and CRiTT, while the CEDA test was limited to 30 minutes.

The data were analysed with IBM SPSS (v.25) software. Cronbach's alpha coefficient was used to assess test reliability. Descriptive statistics applied in finding significant relationships between variables included the mean score of dependent variables, univariate analyses of variance, multivariate analyses of variance and multiple regression analysis.

RESULTS AND DISCUSSION

One hundred and ten mechanical engineering undergraduate students were involved in this study. There were more male than female students, which is typical for engineering disciplines, such as mechanical engineering.

The critical thinking questionnaire measured students' beliefs and attitudes about critical thinking on three subscales: confidence in critical thinking; valuing critical thinking; and misconceptions. The scale for misconceptions was reversed, which means that a lower score represents a better understanding of misconceptions.

Students' confidence in critical thinking and valuing critical thinking was above the average of 5.5, with means (*M*) of 6.76 and 6.98, respectively; and standard deviations (*SD)* of 1.03 and 1.28, respectively. A scale of critical thinking is of special importance, because it might predict a student's grade point average in addition to that predicted by aptitude-based measures as was argued by Stupple et al [17]. Also it can predict creative design assessment scores as argued by Avsec and Ferk Savec [14]. Students' knowledge about misconceptions was found to be below average (*M* = 5.86, *SD* = 1.64) as needed for successful conceptualisation of the engineering design process. Learned misconceptions might significantly enhance design thinking by reducing cognitive fixations, and hence boost variations in design and enhance perceived usefulness of the products, as argued by Avsec and Ferk Savec [14], and by Crilly [18].

Critical thinking is oriented to judgment, which involves evaluation. However, design thinking sometimes requires valuation instead of evaluation. Thus, students' performance in ideational behaviour might reveal factors affecting uniqueness and usefulness of the products or designs. Students' performance in general ideation was above the mid-point (*M* = 3.28, *SD* = 0.52), while the task switch ability was below the average (*M* = 2.66, *SD* = 0.52), where the scale mid-point was 3. Task switch ability can enhance creativity by reducing cognitive fixation [18].

Table 1 shows students' results on design tasks, measured by CEDA, on four subscales. In toto, the mean score was *M* = 106.62 (*SD* = 23.32).

Table 1: Means (*M*) and standard deviations (*SD*), minimum and maximum scores, on the CEDA test (*N* = 110).

CEDA subscales	*M*	*SD*	Minimum score	Maximum score
Fluency	32.91	9.91	7.00	64.00
Flexibility	27.17	7.43	7.00	49.00
Originality	27.14	7.73	6.00	48.00
Usefulness	19.40	2.93	6.00	24.00

Engineering design is about both creation and design. A self-motivated student with good spatial reasoning, visualisation and knowledge of technology will persist with problem finding and solving, and thus succeed in engineering design [10][14][21][22].

Regression Analysis

For regression analysis it was hypothesised that students' critical thinking may affect their ideational behaviour. A linear relation between independent (predictor) and dependent (criterion) variables was assumed. Regression coefficients (β) considered had significance of $p < 0.05$. Students' confidence in critical thinking was found as a significant and strong predictor ($p = 0.000 < 0.05$) in their general ideational behaviour ($t = 3.93$, beta weight $\beta = 0.36$).

Critical thinking moderately predicts task switch ability ($p = 0.048$, $t = 1.97$, $\beta = 0.22$), while misconceptions significantly ($p = 0.004 < 0.05$) and strongly negatively predict students' task switch ability ($t = -2.93$, $\beta = - 0.28$). These findings point to the importance of motivation (valuing critical thinking), both intrinsic and extrinsic for improving design ability and the importance of misconceptions in providing unique and useful design. Factual and conceptual declarative knowledge with the procedural interact with motivation to increase students' creation of new content needed for the design process and to think creatively [10]. A strong correlation was also found between both factors of ideational behaviour, where general ideation significantly ($p = 0.000 < 0.05$) predicts task switch ability ($t = 5.87$, $\beta = 0.49$).

An hypothesis was that the ideational behaviour of students could have a predictive value for creative engineering design. Since design thinking is based on real products and processes and not only on abstract divergent thinking, which is reflected in the fluency and flexibility of ideas, originality of designs and their perceived usefulness can be expected as a crucial factor for design thinking. Regression analysis revealed non-significant ($p > 0.05$) predictive values of ideational behaviour in the subscales of fluency and flexibility of design.

As expected, the analysis revealed significant predictive values of general ideational behaviour ($p = 0.018$, $t = -2.40$, $\beta = -0.26$) and task switch ability ($p = 0.031$, $t = 2.19$, $\beta = 0.24$) in the perceived usefulness of designs. Moreover, general ideational behaviour significantly predicts originality or unusualness of designs ($p = 0.019$, $t = 2.39$, $\beta = 0.25$).

A summary of multiple regression analyses is shown in Figure 1.

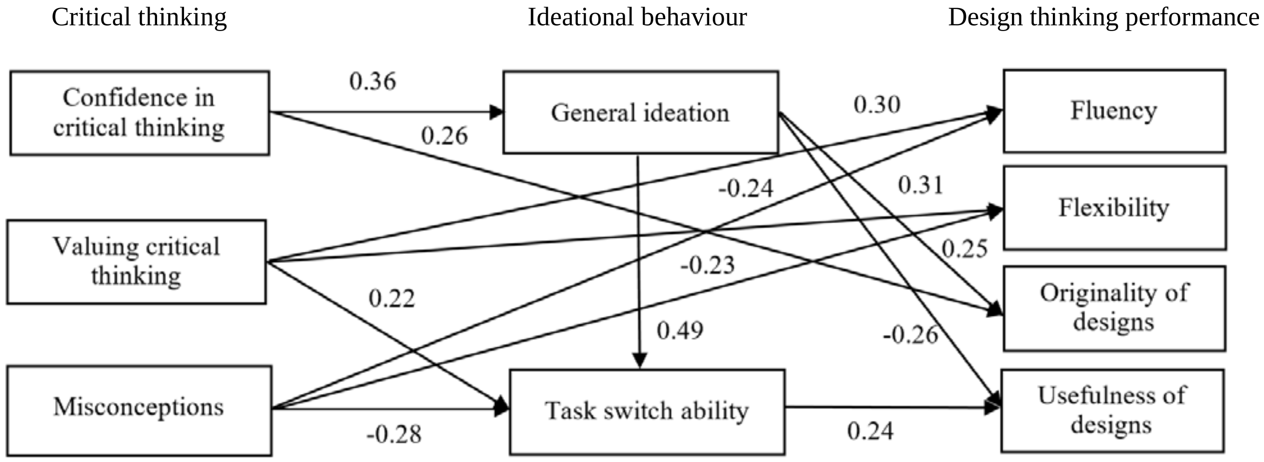

Figure 1: Students' attitude and beliefs towards critical thinking regressed on ideational behaviour and design thinking supported by ideational behaviour regressed on design thinking. Path coefficients are statistically significant at $p < 0.05$ ($N = 110$).

As shown in Figure 1, some direct effects of critical thinking on design thinking were found. Confidence in critical thinking might significantly predict originality of designs ($p = 0.007$, $t = 2.77$, $\beta = 0.26$), while valuing critical thinking and misconceptions learned have a predictive value on fluency of design ideas ($p = 0.002$, $t = 3.26$, $\beta = 0.30$; $p = 0.009$, $t = -2.66$, $\beta = -0.24$, respectively) and in flexibility of design ideas ($p = 0.001$, $t = 3.28$, $\beta = 0.31$; $p = 0.011$, $t = -2.59$, $\beta = -0.23$, respectively).

CONCLUSIONS

Design thinking as an educational approach has potential in several disciplines, by enabling innovation to promote sustainability in natural, economic and social environments. Design thinking is largely influenced by critical thinking directly and indirectly. This is reflected in students' confidence in critical thinking, their motivational beliefs and misconceptions, which enhance idea generation and the evaluation of creative designs. Results also indicated that intrinsically motivated students with task switch ability can make more useful designs and overcome design fixations.

Design thinking has also been found as an approach that can deal with different motivational requirements of different tasks; students can alternate different phases of design thinking, iterate them at will and regrade them to different degrees of awareness and meta-motivational sensitivity. This is a future direction of research.

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