Engineering Design Innovation through C-K theory based Templates

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Abstract

Undergraduate engineering education must train students to not only solve design challenges that transcend disciplinary boundaries, but also communicate, transfer knowledge, and collaborate across technical and non-technical boundaries. One approach to achieving this goal is teaching bio-inspired design (BID) in an engineering curriculum. In teaching bio-inspired design, the Concept-Knowledge (C-K) theory is a well-established approach for integrating multiple domains of information and facilitating innovation through connection building. For the purposes of evaluating the benefits of using C-K theory and their application to design innovation, students in sophomore engineering are assigned a design project using C-K theory template. This paper discusses the adoption of Concept-Knowledge (C-K) theory template for student's use in sophomore design course at both the University of Georgia, Athens (UGA) and the James Madison University (JMU) for design innovation in undergraduate engineering curriculum. Statistical analysis of student's work based on the C-K theory template was carried out to investigate the relationship to design innovation. The results obtained are presented and discussed. Results from the analysis suggest that the C-K theory based approach improved students abilities to design and develop innovative solutions.

Introduction

The increasingly interdependent global marketplace has intensified competition in manufacturing and service sector industries. The survival of these industries is highly dependent on their ability to develop sophisticated and innovative products or services. There is thus a critical need for skilled engineering who are adequately prepared to excel in today's challenging and competitive business environment and who can address societal, environmental, political and business needs [1]. Engineering education researchers have identified that future generations of engineers will need to have advanced problem-solving skills, teamwork skills and a zeal for developing new products and processes as well as the capability to understand social and environmental requirements in engineering [2]. One of the engineering education models proposed for the enhancement of engineering education suggests that training engineering students in multidisciplinary engineering areas will improve their ability to generate innovative solutions to engineering design problems [3-5].

Several institutions (for example, Oregon State University, University of Georgia, James Madison University, Purdue University, Clemson University, Penn State University-Erie, University of Maryland, Indian Institute of Science, University of Toronto, and Dalhousie University, Ecole Centrale Paris) are adopting bio-inspired design concepts to educate students on design inspiration and innovation. Many computational and framework based approaches were developed to teach bioinspired design courses to engineering students. Chakrabarti et al. developed a computational tool for generation of novel design solution [6]. Nagel et al. proposed functional modelling approach to capture unique functional feature [7]. TRIZ based models were also proposed for the effective mapping of analogies in bioinspired design process [8]. The design solutions to complex engineering problems in mechanical, electrical, electronics, and civil engineering fields for example can find additional inspiration when biomimicry concepts are integrated into the design process [9, 10].

In the context of implementing multidisciplinary teaching and improving the undergraduate education, the Concept – Knowledge (C-K) theory [11] was introduced in the sophomore design course in engineering curriculum at UGA and JMU to investigate the design innovation aspects through projects. This study uses quantitative analysis techniques to address the research gap in demonstrating the capability of C-K theory-based templates used in bioinspired design process to produce innovative design solutions. The engineering design performance scores and data related to a student design project were mapped on the C-K theory template, and a statistical analysis was carried out. Performance scores were assigned to design engineering attributes following an evaluation criterion. In the next sections, a brief overview of C-K theory as well as the data analysis performed and the results obtained are presented and discussed.

C-K Theory Approach to Bioinspired Design

We have adopted the Concept-Knowledge (C-K) theory [11, 12] as a theoretical framework to introduce bio-inspired design to sophomore students that integrates creative thinking and innovation. This C-K theory approach utilizes two interdependent spaces: (1) The knowledge space (K) – a space containing propositions that have a logical status for the designer (i.e., all available knowledge); and (2) The concepts space (C) – a space containing concepts that are propositions, or groups of

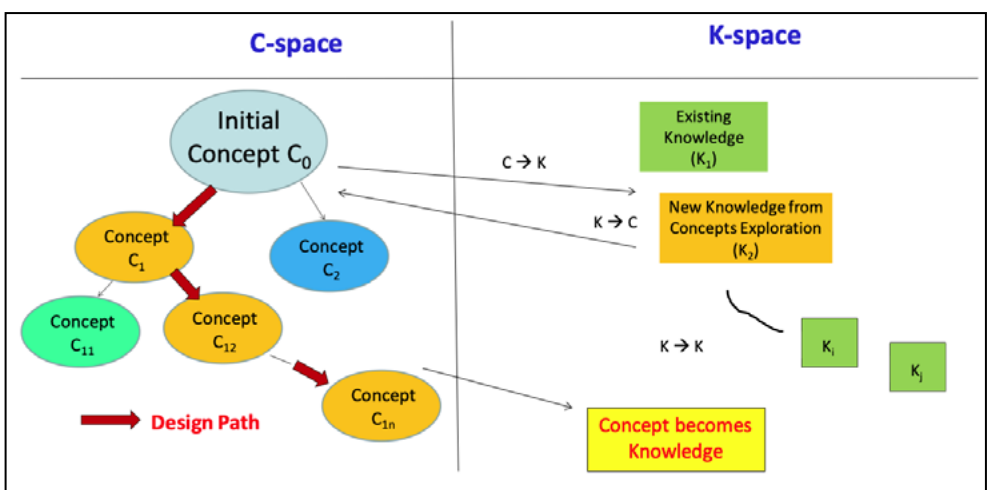

Figure 1. An overview of C-K theory for bio-inspired design

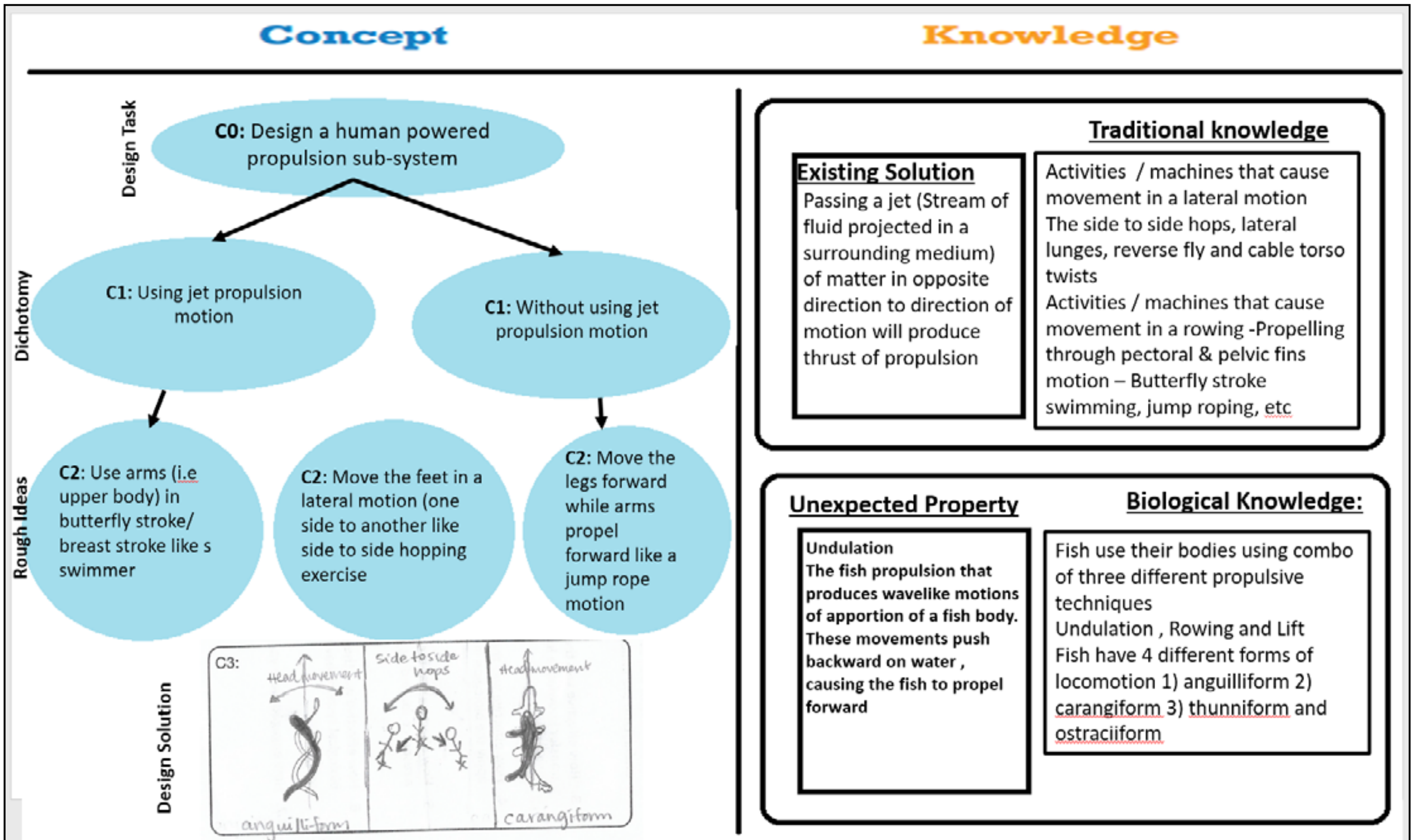

Figure 2. Typical C-K map

propositions that have no logical status in K (i.e., have yet to be verified by knowledge) as shown in Figure 1. The knowledge space was created with biological information and scientific and engineering principles. The logical integration of objects in concept and knowledge space was completed with C-K operators. The CàC, KàK, KàC and CàK operators were used to represent generation of concepts from concepts, knowledge from knowledge, concept from knowledge and new knowledge from concept respectively [12]. C-K theory emphasizes connection building as well as exploration and expansion of both spaces to iterate to a better solution. Knowledge is therefore not restricted to being a space of solutions, but rather it will be leveraged to improve our understanding of the innovative designs. Moreover, C-K theory requires explicit documentation of the design path, thus inherently modeling cross-domain linkages and is adaptive to multiple domains making it amenable to a wide range of engineering problems.

Research Methodology and Implementation

The C-K theory based template was implemented at the conceptual design phase through a design project at the UGA and JMU in a sophomore design course, and at in a sophomore engineering design course that focused on the theory, tools, and methods of the engineering design process. This section describes those courses, and how the C-K theory template was used in projects for assessing the design innovation through design engineering attributes.

University of Georgia

Students in three engineering (Agricultural, Biological and Computer Systems) majors are taking the sophomore engineering design methodology course in every spring semester since 2016. It is a two credit hour course (meets once a week for about 2 hours) and provides an introduction to design methodology, emphasizing the design process starting from design need to requirements, conceptual design and evaluation and prototype testing. In addition to traditional homework and a mid-term test, a final project was assigned for students to demonstrate and implement the design methodology. In order to emphasize the innovative and creative aspects of design solutions during the conceptual design phase, students are introduced to bio-inspired design and are required to use - C-K theory in generating design solutions for their projects. Students are exposed to bio-inspired design and C-K theory through lectures as well as examples in class by the instructor. The instructor gives lecture on bioinspired design process, and after that students are exposed to in-class assignment as well as final project requiring them to complete bioinspired design using C-K theory template. Students work individually as well as in teams in completing the template.

James Madison University

The sophomore engineering design course sequence, Engineering Design I and II, is the cornerstone of the JMU design sequence curriculum. The objective of the course sequence is to not only teach students the design process, but also to drive students toward ownership of the engineering design process as well as provide the base knowledge to begin their capstone projects. To achieve this objective, a yearlong, client-based, design project is woven into instruction in the area of engineering design theory and methodology. All assignments in the sophomore engineering design course tie to the yearlong course project, including the bio-inspired design assignment. To integrate bio-inspired design into the human powered vehicle design project each member of a team applies bio-inspired design to a different sub-system (e.g., propulsion, steering, braking) of their design to showcase a variety of design problems and analogies that enable bio-inspired design. All students complete the C-K mapping template three times, twice in class as part of a learning activity during lecture to understand the process of discovery, and again in their assignment to scaffold application to the human powered vehicle.

Study Details

The C-K theory based template was implemented through a design project involving to create a human powered propulsion system both at JMU and at the

Designation of Design Engineering Attributes of UGA and JMU data
Innovation (U_DE1 & J_DE1)
Imagination (U_DE2 & J_DE2)
Decision making (U_DE3 & J_DE3)
Active participation (U_DE4 & J_DE4)
Redesign and Improvement (U_DE5 & J_DE5)

Table 1. Design engineering attributes

Scale Value	Criteria
4	For well-defined / described concepts with higher order of creativity and with well-defined design path
3	For moderate explanation of concepts with moderately defined design path
2	For lower level explanation of concepts with roughly defined design path
1	For the poor explanation of concepts with unclear design path

Table 2. Design performance evaluation criteria

UGA. Students were asked to record their biomimicry-based design solution on a Concept-Knowledge (C-K) template as shown in Figure 2. In this project example, the design solution for a human powered propulsion system was inspired by fish body movement. The biological knowledge object in C-K map was used to explore the biological system and also to identify the unexpected property, which helped the fish to maneuver in forward and backward directions. The design concepts developed by integrating inspiration from the biological system and the traditional knowledge system were mapped into the concept space. The concept space in the C-K map was created with design concepts developed from a merging of traditional and biological knowledge and was connected logically using different C-K operators to represent the evolution of bioinspired design solution concepts.

Evaluation of students' design performance based on C-K theory template

In the context of developing an assessment methodology to understand the design learning skill of the students, the C-K theory based design process was characterized as the ability to iterate their imagination during conceptual design process. At the end of conceptual design process, a design decision was made to choose a proper design path that would lead to design solution, to get a solution that need minor design improvement, and to result with innovation design concept or design solution [13]. The design learning skill attributes to evaluate student performance were defined as innovation; imagination; decision-making; active participation; and redesign and improvement as presented in Table 1. The criteria for design concepts/innovation evaluation (from 1 to 4) as described was given in Table 2. The performance score reflecting the design engineering attributes matrix f or statistical analysis was prepared by grading design learning attributes on a scale from 1 to 4 for all the students from both UGA and JMU [14].

The performance score data of C-K theory template based design solutions from 53 JMU students and 48 UGA students were analyzed. Scores were assigned based on student performance on innovative design and development competencies to achieve feasible design solutions. The C-K theory template completed by a student (see Fig. 3), the basis for assigning the scores (1 – 4) for various design attributes are shown in Table 3. This is based on students' competence in effectively translating biological knowledge into the design solutions.

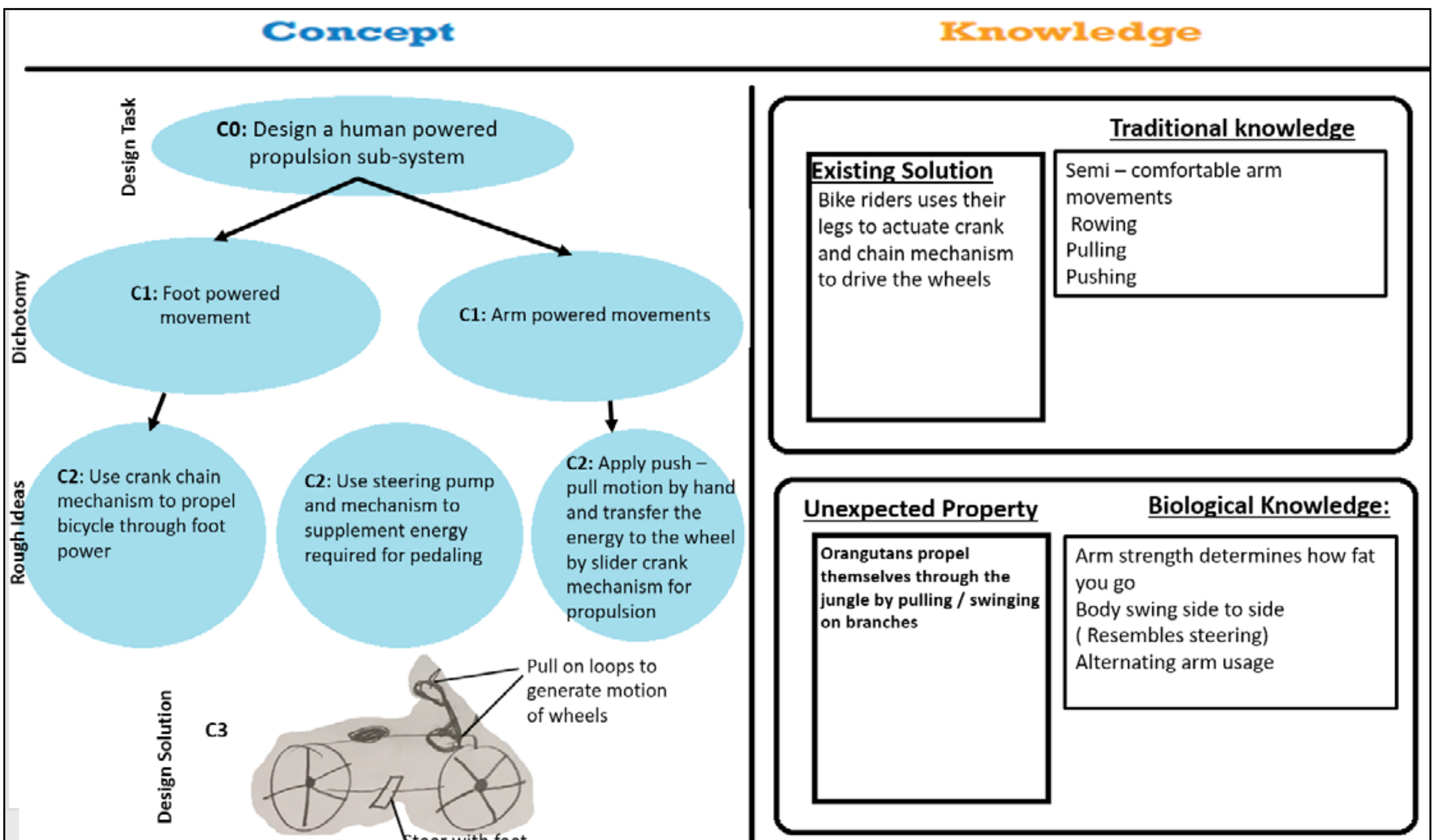

Figure 3. Sample C-K map for the demonstration of design process evaluation

Table 3. Student's performance evaluation on design engineering attributes		
Design Attributes	**Design performance / Evaluation observations**	**Assigned Score**
Innovation (DE1)	The propelling concept presented is new/novel and feasible for evolution.	4
Imagination (DE2)	New concept of propelling a bike is perceived from biological source	4
Decision making (DE3)	Conclusion shall include suggestions for incorporating aerodynamic shapes in propeller for better propelling	3
Active participation (DE4)	Design Process is presented well in CK map	4
Redesign and improvement (DE5)	Needs to include suggestions in propeller design for product realization and improvement	3

Table 3. Student's performance evaluation on design engineering attributes

Results and Discussion

Assessment of student work was completed using a C-K theory template and the design engineering attributes and statistical analysis was performed through student's "t" test and principle component analysis. The relationship between the two data sets (UGA and JMU) and their population was studied by conducting student's t- test with the null and alternate hypothesis. The datasets used for this test were obtained by normalizing the observations of JMU and UGA students' scores on each of the design attributes. Based on the results from Student's "t" test, it was found that the mean vectors of two data sets from JMU and UGA, respectively are from the same population.

The results of student's performance on design attributes mapped through the C-K template are presented in Fig. 4. The probability distribution function for each design attribute of UGA and JMU data showed that the design engineering attributes Innovation (U_DE1 & J_DE1) and Imagination (U_DE2 and J_DE2) had wide distribution. The peak value of normal distribution function for the all attributes occurred on the right side of the performance score value 2.5. Further, it was observed that the peak values of design attributes of UGA and JMU data, U_DE1, U_DE2, J_DE1 and J_DE2 were close to the maximum design performance score value of 4. This revealed that the mapping of bioinspired design process on the CK map has significant capability to produce innovative solutions.

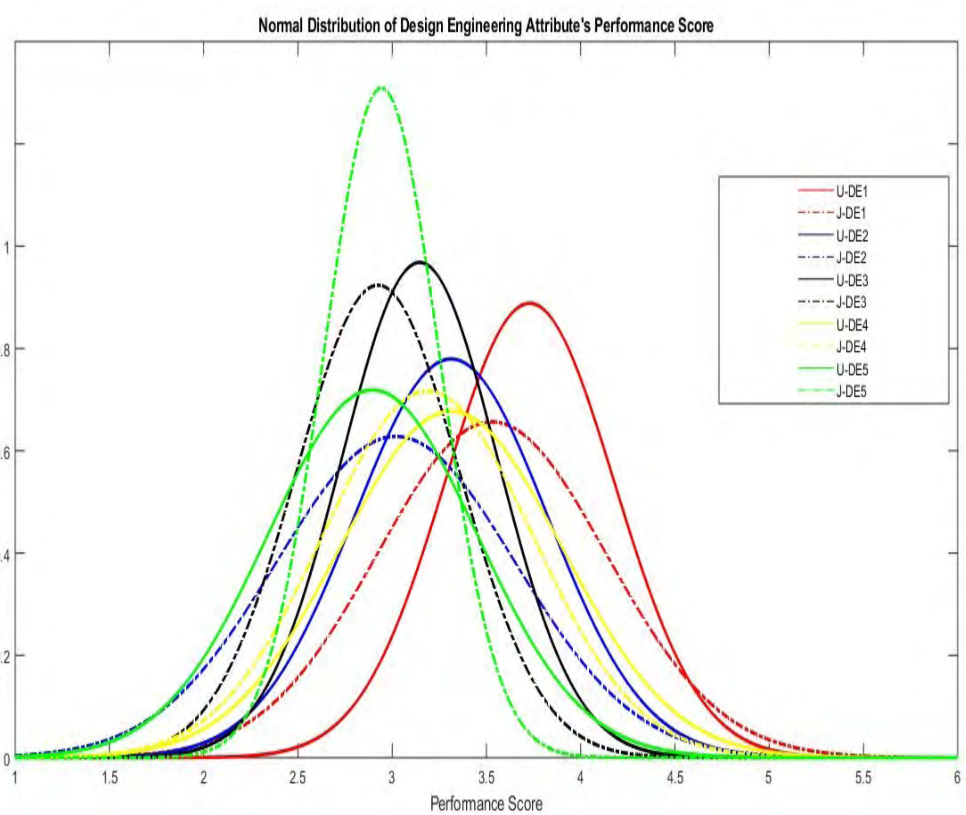

Figure 4. Normal distribution of students' performance score on each design attribute

A Principal Component Analysis (PCA) was performed to reduce the dimensions of the dataset and to identify the best representative attributes reflecting the design engineering attributes. The observations were transformed to the principal direction where the variance is maximal. The first two principal components that explained more than 60% of variance of JMU and UGA datasets were identified and the biplot of these principal components (PCA1 and PCA2) with transformed observations was plotted as shown in Figure 5 to visually see the relationship among various design-engineering attributes between UGA and JMU.

In biplot, all the five attributes were appeared in the positive region for the first principal component space of the JMU and UGA datasets. While, the second principal component was considered to explain the datasets with maximum variance, only attributes innovation and imagination (DE1 and DE2) of JMU dataset and attributes innovation, imagination and redesign and improvement (DE1, DE2 and DE5) of UGA dataset were retained in positive region. This indicated that the entire datasets could be represented by the observations recorded in DE1 and DE2 attributes of JMU dataset and DE1, DE2 and DE5 attributes of JMU dataset. In other words, design solutions obtained by the JMU and UGA students were result of their abilities attributed by innovation and imagination. The PCA also indicated that the UGA design solutions or design concepts need less improvement to obtain the maturity level.

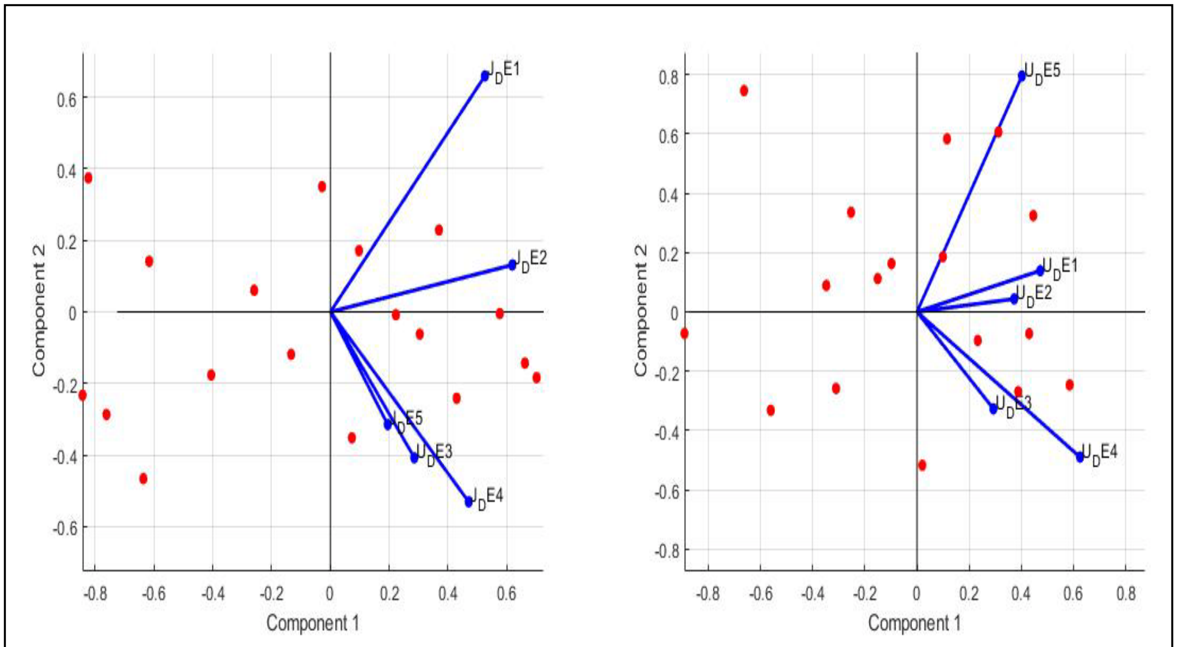

Figure 5. PCA plots of JMU and UGA datasets

Conclusion

Teaching bioinspired design courses to engineering undergraduate students were investigated by several researchers in the context of innovative design solutions, multidisciplinary courses, design thinking enhancement and design solution evolution from biological knowledge resources. Although many researches discussed about searching mechanisms, analogical retrieval, exploration of design strategies and mapping techniques to transform biological information into a functional model, it is still lagging in identifying a suitable model for BID course. The C-K theory based approach is a concept and knowledge space exploration and expansion process that maps design solution evolution more effectively and had been proposed by researchers as a simplified approach for understanding biological system, searching the analogies, identifying suitable solution and mapping of solution through transfer of information or knowledge [14, 15]. Hence, in this study, we analyzed the design solutions mapped in concept – knowledge (C-K) space using statistical methods to evaluate BID process capability to produce innovative design solutions in student projects. The various statistical tests were carried out on the students data collected from UGA and JMU. It was found from student's t- test that both the dataset samples were from the same population; hence, C-K theory based design process performance would not be affected by differences attributed by different universities. The normality and PCA tests revealed that the C-K theory based design process had significant capability to produce innovative design solutions. Among the five engineering design attributes considered for both UGA and JMU data sets, Innovation and Imagination were identified as the most important attributes reflecting student performance. These findings suggest that the C-K theory based template can be adopted in engineering design courses to stimulate innovative design solutions, and could be integrated into the engineering curriculum to train students at various institutions.

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References

1. Andriopoulos, C. and M.W. Lewis, Managing Innovation Paradoxes: Ambidexterity Lessons from Leading Product Design Companies. Long Range Planning, 2010. 43(1): p. 104-122.
2. Franchetti, M. and S. Ariss, The Implementation of Senior Design Capstone Projects Combining Engineering and Business Students. Vol. 17. 2016.
3. Sirinterlikci, A., et al., A Multi and Cross-Disciplinary Capstone Experience in Engineering Art: Animatronic Polar Bear. 2019.
4. Borchers, A., et al., Bringing Environmental Sustainability to Undergraduate Engineering Education: Experiences in an Interdisciplinary Course. Vol. 13. 2012.
5. Nagel, J., et al., Bio-inspired Design Pedagogy in Engineering. 2019. p. 149-178. Lurie-Luke, E., Product and Technology Innovation: What can Biomimicry Inspire? Vol. 32. 2014.
6. Chakrabarti, A., et al., A functional representation for aiding biomimetic and artificial inspiration of new ideas. 2005. 19(02).
7. Nagel, J., R. B Stone, and D. McAdams, Function-Based Biologically-Inspired Design. 2014
8. Trotta, M.G., Bio-inspired Design Methodology. International Journal of Information Science, 2012. 1: p. 1-11.
9. Nagel, J., R. L. Nagel, and M. Eggermont, Teaching Biomimicry with an Engineering-to-Biology Thesaurus. Vol. 1. 2013.
10. Nagel, J. and R. M. Pidaparti, Significance, Prevalence and Implications for Bio-Inspired Design Courses in the Undergraduate Engineering Curriculum. 2016. V003T04A009.
11. O Kazakçı, A., A. Hatchuel, and B. Weil, A model of CK design theory based on term logic: A formal CK background for a class of design assistants. 2008.
12. Sharif Ullah, A.M.M., M.M. Rashid, and J.i. Tamaki, On some unique features of C–K theory of design. CIRP Journal of Manufacturing Science and Technology, 2012. 5(1): p. 55-66.
13. Dym, C.L., et al., Engineering Design Thinking, Teaching, and Learning. 2005. 94(1): p. 103-120.
14. Nagel, J.K., et al., Teaching bioinspired design using C–K theory. Bioinspired, Biomimetic and Nanobiomaterials, 2017. 6(2): p. 77-86.
15. Nagel, J., et al., Board # 107 : Teaching Bio-inspired Design Using C-K Theory, in ASEE Annual Conference & Exposition. 2017.

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