Leveraging Design Thinking to Enhance Engineering Teaching: An Operational Model

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Abstract*—*Contribution: **The proposed operational model offers a detailed framework for understanding the complexities of design thinking. It helps instructors evaluate each stage, promoting the development of high-quality designs. This model emphasizes the link between the various stages and the final design quality, steering students toward achieving outstanding results.**

Background: **Design thinking benefits students across almost all majors by promoting critical thinking, creativity, and teamwork. It places a strong emphasis on the user's needs and involves testing and refining prototypes with empathy for the user. While easy to grasp, its practical application poses complex challenges, particularly in engineering and science education.**

Intended Outcomes: **This study examines the challenges of teaching design thinking and proposes an operational model to represent the design process.**

Application Design: **The model incorporates a "spring system" to demonstrate potential variations in the design process, including the number of user-centered design (UCD) methods used, the size of the problem/solution space, the difficulty or resistance to transitioning between activities, and time spent on each activity.**

Findings: **Two projects illustrate the use of the model. Using the proposed metrics, the design process can be established, and the operational model can control the learning process while enhancing the consistency and quality of the design outcome. Future empirical research should validate the model's effectiveness, address biases, and foster critical thinking and diverse perspectives within student teams.**

***Index Terms*—Creative thinking, design for humanity, design teaching, empathetic design, human-centered design.**

I. BACKGROUND OF DESIGN PROCESS

ENGINEERING education frequently draws from theories and methods from other fields, encouraging educators to broaden perspectives beyond a single discipline, especially in product development [1]. Among the various product design and development frameworks that exist, Design thinking stands out because it prioritizes the user, unlike traditional value chain approaches that start with manufacturer capabilities or customer specifications [2], [3], [4], [5]. Focusing on the user provides insights into their needs, thoughts, emotions, and motivation, which lays the foundation for problem framing, reframing and ideation. Framing and reframing involve the important process of defining and subsequently redefining problems to uncover new perspectives, while ideation is the process of generating creative solutions and ideas.

Despite its present-day popularity, Design Thinking is not a novel concept. Its roots can be traced back to the 1960s, or possibly even earlier, when individuals first started exploring the scientific principles of design and its diverse elements [6]. Over time, it has evolved into its many variations, including the Stanford d.school framework, IDEO's human-centered design, IBM's design thinking, Google's design sprints, and the double-diamond process from the British Design Council to name a few. One fundamental commonality in all these methods is the divergence and convergence in the two diamonds (Fig. 1), where the first diamond identifies the problem while the second diamond hones in on a solution to the reframed problem. Divergent and convergent thinking are also not new concepts; they are part of the human problem-solving process [7], and an important aspect of creative thinking and idea generation [8], [9], [10].

The design thinking process typically involves five stages: 1) empathize (diverging); 2) define (converging); 3) ideate (diverging); 4) prototype (converging); and 5) test (converging) (Fig. 1). Empathize and define form the first diamond (the problem), while ideate, prototype, and test are the second diamond that leads to the solution. Such a structured approach ensures a comprehensive understanding of the problem and enables the iterative development of solutions. Evaluating the design process involves assessing each stage, focusing on how effectively they address user needs, encourage creativity, and produce effective and viable solutions. Even though the design thinking process can vary, the main idea is the same: it focuses on the problem and the user. Every version starts with understanding the problem well and ends with a tested product or service.

II. DESIGN THINKING IN EDUCATION

Design thinking is taught at all levels, from elementary school to university, to foster creativity and problem-solving skills in students [11], [12], [13], [14], [15], [16]. Its implementation is driven by the belief that it promotes adaptability and fosters innovation [17]. However, teaching and learning design thinking is complex and demands significant effort from both teachers and students. Diverse student backgrounds and mental models, spanning fields like art, engineering, and business, challenge creating an inclusive learning environment that encourages divergent and disruptive thinking. This process is

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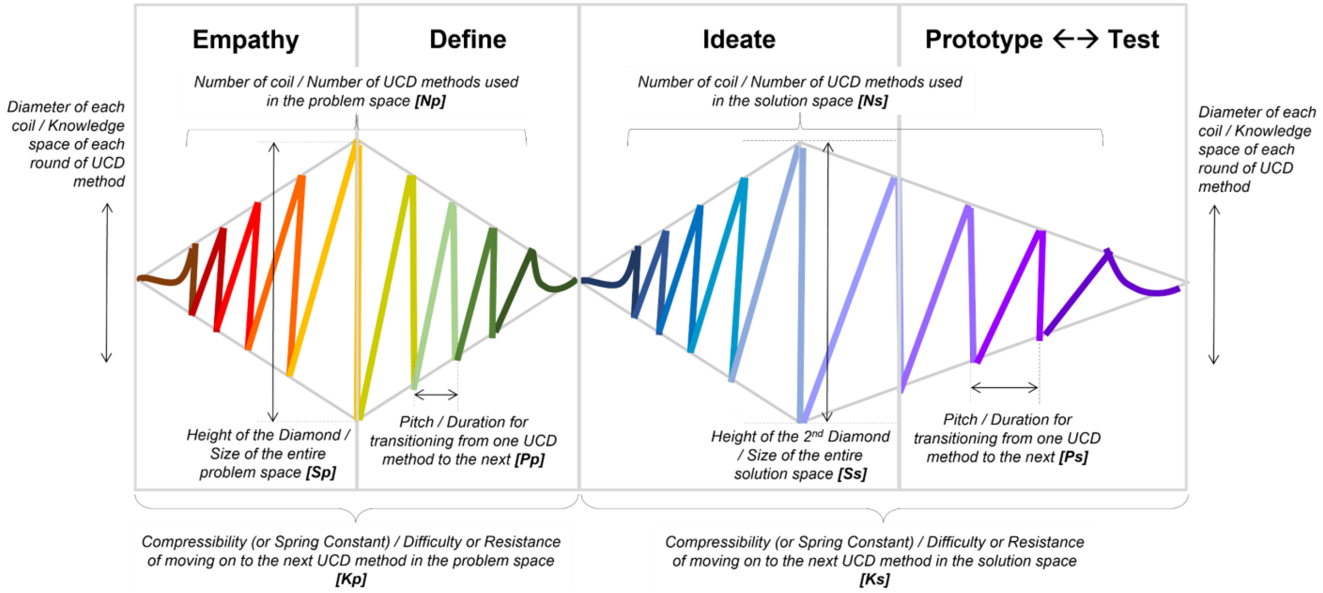


Fig. 1. Generic view of the operational model of design thinking.

further complicated by technological issues, resource intensity, and the need for specialized training and assessment methods [18], [19], [20], [21], [22]. Thus, a tailored approach with multiple teaching formats is essential to meet diverse learner needs [18]. Furthermore, there is no method to evaluate the complexity of the students' design processes, the effectiveness of the various methods used, or their impact on the final result. Thus, the primary aim of this article is to address the many challenges associated with teaching design thinking by proposing a comprehensive operational model. The basis for this model is a mechanical spring system analogy, as the related metrics in a spring can help evaluate how effectively students use design thinking tools to achieve specific learning outcomes. Specifically, the metrics help students.

1) Identify real-world problems through interactions with users and the environment.
2) Develop a mindset and attitude to discover useful, feasible, and viable solutions iteratively.
3) Learn to solve the identified problem by working in interdisciplinary teams.
4) Develop and validate proof of concepts.

The proposed operational model can be applied to the five stages of design thinking and includes user-centered design (UCD) concepts, emphasizing empathy and user feedback. It has practical implications for instructors seeking to integrate design thinking into their curricula, as it provides a structured approach and concrete metrics for evaluation. A case study further exemplifies this model, highlighting its practical application.

III. OPERATIONAL MODEL OF DESIGN THINKING PROCESS

In education, Bloom's Taxonomy [23], [24] provides a way to assess learning outcomes or end results by categorizing them into six levels: 1) knowledge; 2) comprehension; 3) application; 4) analysis; 5) synthesis; and 6) evaluation. While outcomes are important, active learning involves more than just achieving the end result; it encompasses the entire process leading up to it [25]. Therefore, instructors need more guidance to facilitate this journey and achieve the desired outcomes effectively. To better understand how the design process influences the outcome, the proposed operational design thinking model captures and visualizes the variations in the processes used. The model serves as an effective evaluation tool, helping to identify the execution patterns, specific design activities, and methodologies used during the design process rather than just the end result.

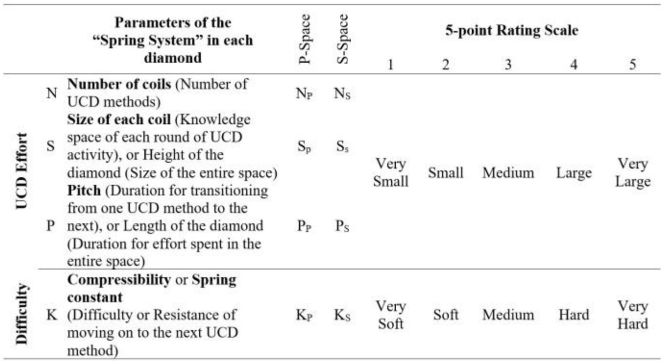
The iterative process of the five stages of the design thinking process (empathy, define, ideate, prototype, and test) illustrated in Fig. 1 can be represented with an analogous spring system operating within each of the two diamond shapes, characterized by the following parameters.

1) Number of Coils (**N**) analogous to the number of UCD methods used, Size of Each Coil (**S**) or the height of the diamond representing the knowledge space of each UCD activity, Pitch (**P**) or the length of the diamond representing the duration of transitioning from one UCD method to the next.

   Each of these three parameters will be rated on a 5-point Likert scale with anchors of Very Small, Small, Medium, Large, and Very Large.
2) Compressibility or Spring Constant (**K**) represents the difficulty or resistance in moving to the next UCD activity. This would be rated on a 5-point Likert scale with anchors of Very Soft, Soft, Medium, Hard, Very Hard.

The scales comprise three ratings (N/S/P) within the problem space (P-Space), assessing the UCD effort dedicated to understanding and identifying the problem to be addressed, as well as crafting a solution to resolve the identified issue within the solution space (S-Space) (Table I). The fourth

TABLE I
PARAMETERS OF THE SPRING SYSTEM IN EACH DIAMOND WITH 5-POINT RATING SCALE



		Parameters of the "Spring System" in each diamond	P-Space	S-Space	**5-point Rating Scale**				
					1	2	3	4	5
UCD Effort	N	**Number of coils** (Number of UCD methods)	N_P	N_S	Very Small	Small	Medium	Large	Very Large
	S	**Size of each coil** (Knowledge space of each round of UCD activity), or Height of the diamond (Size of the entire space)	S_p	S_s					
	P	**Pitch** (Duration for transitioning from one UCD method to the next), or Length of the diamond (Duration for effort spent in the entire space)	P_P	P_S					
Difficulty	K	**Compressibility** or **Spring constant** (Difficulty or Resistance of moving on to the next UCD method)	K_P	K_S	Very Soft	Soft	Medium	Hard	Very Hard

rating (K) assesses the level of difficulty of the problem and solution. The scales provide a quantitative assessment of the effectiveness of the UCD approach and help ensure that both the problem and solution space are adequately addressed. Thus, the result of a project can be represented by a set of two 4-digit combinations, such as (3, 3, 2, 3 and 4, 2, 3, 3), to reflect the level of the UCD effort and the complexity associated with the problem and solution. It should be noted that there could be many confounding factors, such as a person's or group's creativity and effort. These confounding factors are assumed to be controlled with effective team building. What is assessed using these parameters is how well the students use the tools and processes to encompass a wider catch for effective problem solving.

Totaling or averaging the (N, S, P, K) metrics provides an overall evaluation of the design process. This allows instructors to systematically evaluate and compare the effectiveness of different design activities and methodologies, similar to obtaining an overall grade in an examination. By utilizing such an approach, designers can ensure that the final solution adequately tackles the identified problem within the problem space, leading to an overall improvement in the quality and usability of the design. However, care must be taken to ensure that combining these different types of metrics yields meaningful insights into the design process.

The generic operational model in Fig. 1 showcases the utilization of various UCD methods throughout each stage of the design thinking process. The more UCD methods employed, the greater the number of coils. The size of each coil represents the magnitude of the problem (or solution) space the design team focuses on. Upon completing the empathize stage, the design team should have employed various methods to comprehend and relate to unmet needs (such as user research, journey mapping, task analysis, competitive analysis, etc.). The information gathered from these methods should provide the design team with a comprehensive understanding of the entire problem space, as represented by the height of the first Diamond.

The *Define* stage involves consolidating the information gathered in the *Empathize* stage to converge on a well-articulated problem. The design team employs various methods to find patterns and insights (e.g., clustering, abstract laddering, etc.) and challenge assumptions to reframe the problem. The outcome of the multiple methods applied during this stage should aid the team in converging toward a clearly defined problem statement. The speed of this stage may vary, with less reliance on end-users leading to a faster process (i.e., shorter pitch, Fig. 1) or a more complex data set requiring longer time (longer pitch, Fig. 1) to identify patterns and consolidate insights.

The second Diamond encompasses *Ideate*, *Prototype*, and *Test*, beginning with a divergent thinking process to explore a multitude of creative ideas. An idea constitutes any potential solution or approach that addresses the identified problem. The solution space evolves through iterations until the team is content with its scope (height of the second diamond). The convergent process then evaluates and refines the ideas, determining their desirability, feasibility, and viability. While generating more ideas can be beneficial, it may not necessarily be better in all contexts, as the quality and relevance of ideas are crucial. This process may result in several promising solutions for prototyping and testing. The time spent in the divergent and convergent processes may be unequal, resulting in a potentially skewed diamond shape (as seen in Fig. 1).

The design thinking process is nonlinear, with no strict order to UCD activities. Empathy, crucial in design thinking, demands a deep understanding of customers and their needs. The Empathize stage is flexible, often occurring even during iterative Prototype and Test phases to ensure the solution addresses the right problem effectively. Effective training is essential to apply the model appropriately, navigate design thinking's iterative nature, and ensure solutions remain relevant and effective. Various engineering fields can benefit from modified models tailored to specific requirements. The model's flexibility suits design thinking's nonlinear and unpredictable nature, allowing adaptation to diverse contexts and complexities.

IV. CASE STUDY

Since its founding in 2016, the Jacobs Institute for Design Innovation at the University of California, Berkeley has offered the introductory 3-credit course, "Design Methodologies" (DES INV 15), to introduce students to the mindset, skillset, and toolset associated with design. Through guided application, students gain experience in framing and solving problems in design, business, and engineering, as well as learning approaches to noticing and observing, imagining and designing, experimenting and testing, and critique and reflection.

Every semester, 45–65 undergraduate students from different schools and years enroll in the Design Methodologies (DES INV 15) course. Two groups of students from this course are used as a case study to illustrate the application of the proposed method.

During the 14-week semester, they participate in workshops during each class session and submit reflections and weekly assignments. Students go through two innovation cycles, completing two design projects. The first allows them to become familiar with the design thinking mindset, acquire basic

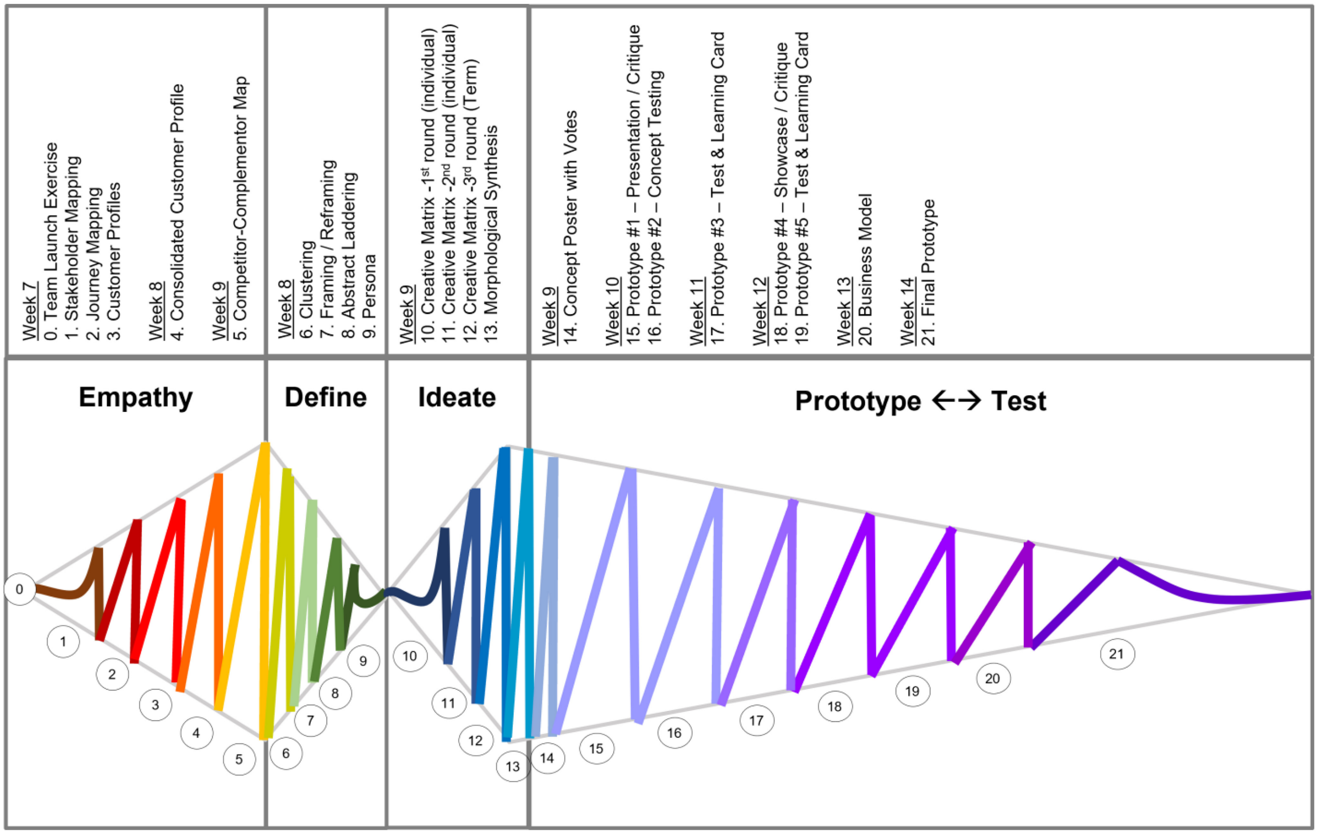


Fig. 2. Operational model of design thinking with 21 UCD methods at different stages for 8 weeks (from 7th–14th week) in the final course project.

skillset, and learn design methods. The topic of the second project is initiated based on the students' preferences, and provides an opportunity to apply and extend the knowledge and skills they have developed during the initial six weeks. At the end of the course, students present their projects in the 14th week, and they are showcased in the Jacobs Design Showcase during the 15th week.

In their final project, students applied UCD methods across different stages of the design thinking process [26], [27], [28]. The design thinking process and the UCD methods that students learned and used are illustrated in Fig. 2, which depicts the various stages of the process from week 7 to week 14.

A. Understanding the User Through Field Research Outside the Classroom

The instructor facilitated the Empathize stage by having each team member collaborate to create an interview guide and conduct individual user interviews to generate journey mappings and customer profiles. By having each team member personally talk to the end-user, this arrangement ensured that everyone was involved in the process of empathy, providing the necessary background knowledge to move on to the Define stage. Some of the students' comments were as follows.

> *"I was surprised by how similar many of our ideas were when it came to the jobs, pains, and gains that we came up with! Great to see that we're thinking along the same lines."*

> *"I was surprised by the similarity my group-mates had for jobs/gains/pains when we did our interviews."*

B. Encouraging Participation and Collaboration in the Design Thinking Process

Before beginning the ideation phase, each team member was given three votes to cast on their favorite "How Might We" (HMW) statements from the nineteen presented in the abstract laddering exercise. (Fig. 3). Considering the whole team, five of these HMW statements were selected for idea generation. In the Ideate stage, three rounds of brainstorming sessions were conducted in a workshop to ensure that all teams were on the same page. A Creative Matrix [13] was used to encourage the students to generate as many ideas as possible. The matrix consists of the problem statements along the Y-axis and tools or ways to help solve them along the X-axis.

1) *First Round:* This was an individual brainstorming session on solving the selected five HMW. Thereafter, the team created the Creative Matrix and posted their ideas. Not every cell may have been filled in this process as it was conducted individually.
2) *Second Round:* This was a continuation of the individual brainstorming session. Having learned the SCAMPER technique (Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Reverse) in the first project, each student was encouraged to use it to generate more ideas [29], [30] to fill-in the matrix's missing cells.
3) *Third Round:* This brainstorming session allowed the students to discuss and exchange ideas within the team.

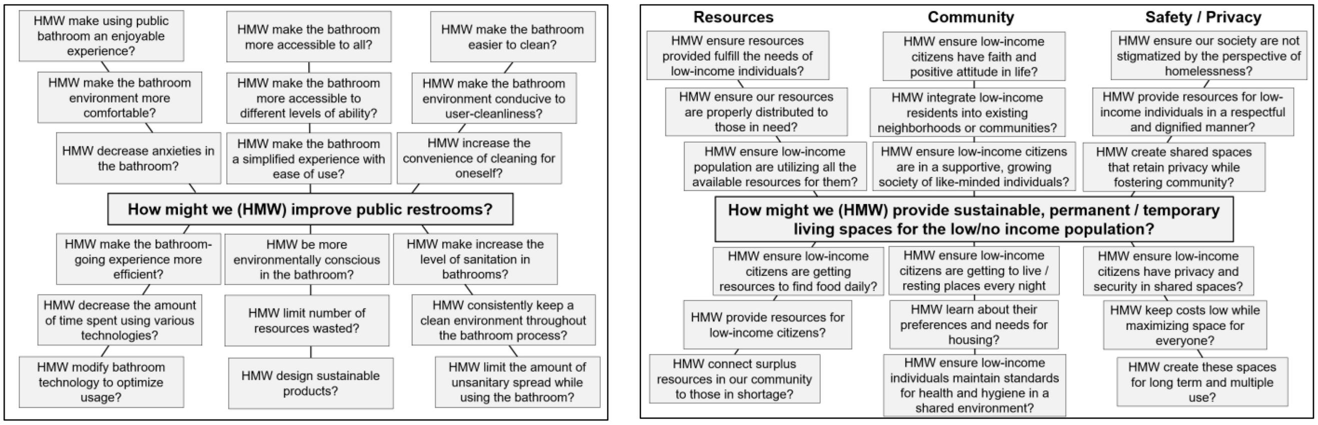


Fig. 3. Week 8 assignment—Abstract laddering (Left: REN; Right: Shellter).

This creative thinking technique helps students explore different facets of an idea by prompting them to consider various ways to alter and improve the existing design.

> *"I was surprised that idea generation was so productive with such a large group"*
> *"I was surprised how many ideas my team was able to come up with throughout the rounds"*
> *"I was surprised to see that our original idea has so many loopholes in it. I think SCAMPER showed us that some of the alternative ideas were actually way more useful, sustainable, and scale-able… "*

Some methods learned in the first project were applied again in the final project, allowing the students to reinforce their understanding and apply the techniques in different scenarios. For example, clustering the observations from interviews and using SCAMPER to generate new ideas.

> "*I relearned the best ways to cluster information and organize it into distinct groups"*
> *"I relearned how to utilize SCAMPER to brainstorm ideas"*

C. Nurturing Acceptance of Feedback From Multiple Sources

The creative matrix generated numerous ideas were further organized and combined randomly using morphological synthesis [12]. Morphological synthesis is a solution-framing method that involves breaking down a problem into its essential components and systematically exploring all possible combinations of these components. This approach enabled the team to construct a high-level system and develop creative options. To do so, the team had to be open to any potential options presented to them. This was followed by the team being encouraged to interact with numerous people to gain feedback from all angles to validate the feasibility of the solutions. From week 9 to 14, each team made at least 6 iterations of prototyping, progressing from rapid and low fidelity to high fidelity. Throughout each development iteration, the team gathered feedback from various groups, aiming to quickly identify what did not work and improve their approach efficiently.

1) *Week 9—Concept Poster:* The concept was presented in class, prompting classmates to vote for their preferred ideas among the solutions offered.
2) *Week 10—First Low-Fidelity Prototype:* The refined concept was presented to the class, who then provided feedback on two aspects, "I like ··· " and "I wish ···", through an online questionnaire.
3) *Week 10—Second Low-Fidelity Prototype:* The enhanced low-fidelity prototype was used to solicit feedback from end users.
4) *Week 11—First Mid-Fidelity Prototype:* After obtaining feedback from the end-users, the students usually experienced either increased confidence or further confusion regarding their project. Each team had individual discussions with the instructor to review the project's progress, which proved to be especially beneficial for teams who had become discouraged after speaking to the end users. The team enhanced their design concept through multiple prototyping and testing iterations.

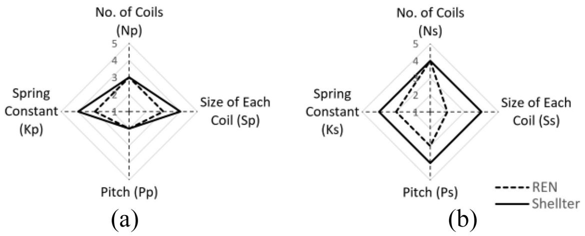
   > *"I was surprised by how well-received our product was with user testing, even though it was a beta testing phase"*
   > *"I plan to improve the prototype significantly along with my group this weekend, especially using the feedback we got from our professor in our meeting with her today"*
   > *"I plan to start ranking more areas of our ideation (e.g., necessary features), to prioritize our workflow"*

5) *Week 12—Second Mid-Fidelity Prototype:* A show-and-tell was held in the classroom, which allowed each team to present their prototype and answer numerous questions from their classmates during the demonstration. This was a highly interactive session and a beneficial opportunity for each team to gain insights from others.

   > *"I learned a lot about the incredible ideas many of my classmates came up with. It was incredible to see the level of progress made by everyone over the course of the last few weeks."*
   > *"I relearned that there is always something that needs to be improved when designing a product."*
   > *"I wonder how I can improve my pitching ability. I listened to many other pitches by other teams*

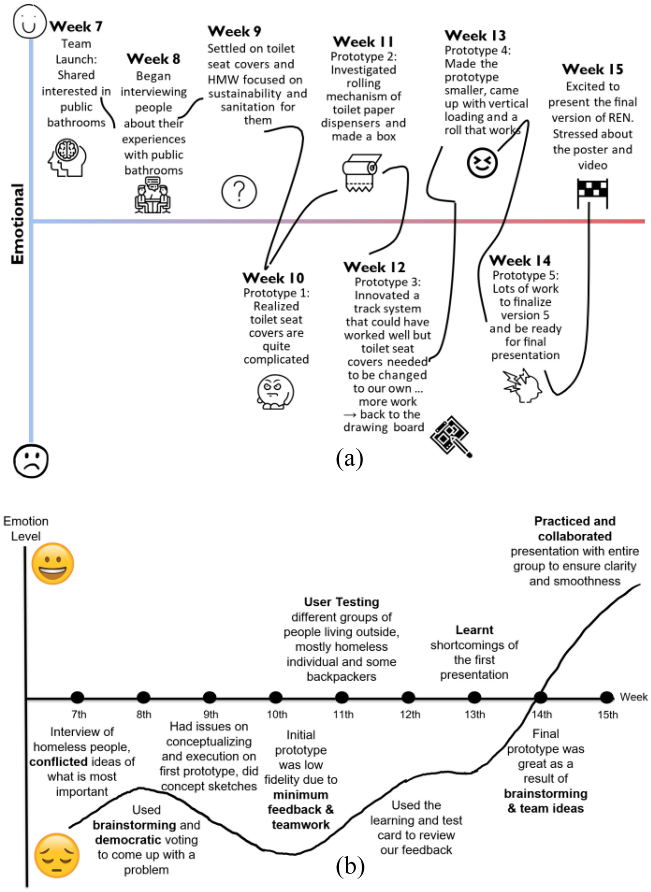
TABLE II
RATINGS ON UCD EFFORTS (N/S/P) AND COMPLEXITY (K) OF THE PROBLEM AND SOLUTION DIVERGENT–CONVERGENT PROCESS FOR REN AND SHELLTER

	Parameters of Spring System	REN	Shellter
1st Diamond (P-Space)	No. of Coils (Np)	3	3
	Size of Each Coils (Sp)	3	4
	Pitch (Pp)	2	2
	Spring Constant (Kp)	3	4
Problem Divergent-Convergent Score = (Np+Sp+Pp+Kp)/4		**2.75**	**3.25**
2nd Diamond (S-Space)	No. of Coils (Ns)	4	4
	Size of Each Coils (Ss)	2	4
	Pitch (Ps)	3	4
	Spring Constant (Ks)	3	4
Solution Divergent-Convergent Score = (Ns+Ss+Ps+Ks)/4		**3**	**4**



(a) (b)

Fig. 4. REN and Shellter ratings in (a) problem space and (b) solution space.



(a)

(b)

Fig. 5. Project team experience journey map from (a) REN and (b) Shellter.

> *and saw that the really successful ones know their products inside out and could answer any question on not just the design but also the business model."*

6) *Weeks 13 and 14—Final Prototype:* The last two weeks were devoted to developing the final prototype, requiring the team to integrate user feedback. Each team had discussions with the instructor to review the project's progress once more, ensuring that every team could achieve their desired outcome in two weeks. If the team encountered any difficulties moving forward, the instructor would provide additional guidance.

Nonlinearity in the design process was a crucial concept during the iterative design process. Those teams who felt uncertain about their solution could revert to their creative matrix or carry out another brainstorming session to generate more ideas. Throughout this iterative design process, the students had to be open to any failures, accept feedback from various audiences, and experiment with different alternatives to realize their design objectives.

D. From Theory to Practice: Making the Most of the Operational Model

Two projects were selected for illustration of the proposed operational model because they met the inclusion criteria of completed assignments and active participation in workshops. Each parameter of the spring model was rated based on each team's performance (Table II) and depicted in a radar chart (Fig. 4). Data for this case study includes student project work from workshops, assignments, presentations, and final outcomes for the showcase. Ratings were assigned based on project work and cross-validated with course grades on related deliverables. Justification of the ratings were collected during project discussions, conversations with individual team members, class reflections, and evaluations of project outcomes. These justifications are based on the UCD effort, including specific design activities and methodologies used during the design process, and the perceived difficulty of the problem and solution as given as follows.

In the 1st Diamond (P-Space) of the design thinking process [Table II, Fig. 4(a)], the assessments were as follows.

1) *UCD Methods Used:* Both teams used 9 UCD methods in 2 weeks, so $Np = 3$ for both REN and Shellter.
2) *Team Size and Data Collection:* REN had four members, while Shellter had five. Shellter collected more valuable user data during Journey Mapping and Customer Profiles (Fig. 2) in the Empathize stage. Thus, $Sp = 3$ for REN; $Sp = 4$ for Shellter.
3) *Method Sequence and Pace:* All teams followed the instructor's instructions to practice nine UCD methods sequentially with a swift pace, resulting in $Pp = 2$ for both teams.
4) *Emotional Experience:* REN experienced positive emotions [Fig. 5(a)], while Shellter faced difficulties during convergence, including engaging target users and team conflicts due to a larger problem scope (Sp). Thus, $Kp = 3$ for REN; $Kp = 4$ for Shellter.

Overall, REN's first diamond (Empathy, Define) had a narrower problem scope, leading to a slightly lower average UCD effort and perceived complexity for diverging and converging (=2.75). Shellter began with a broader problem scope, requiring slightly higher UCD effort and perceived complexity for diverging and converging in the problem space (=3.25).

In the 2^{nd} Diamond (S-Space) of the design thinking process [Table II, Fig. 4(b)], the assessments were as follows.

1) *UCD Methods Used:* Both teams used 12 UCD methods in 6 weeks, so $Ns = 4$ for both REN and Shellter.
2) *Idea Generation:* Following three rounds of Creative Matrix (#10, #11, #12 in Fig. 2), REN generated 38 ideas, while Shellter generated 63 ideas. Shellter required more effort to transform these ideas into workable solutions. Thus, $Ss = 2$ for REN; $Ss = 4$ for Shellter.
3) *Prototyping Approach:* Despite following the instructor's guidance, each team adjusted their prototyping based on user feedback and complexity. REN demonstrated effective iterative cycles, reflected in their emotional state [Fig. 5(a)]. Shellter's attempt to incorporate multiple features extended the process and caused additional stress [Fig. 5(b)]. Thus, $Ps = Ks = 3$ for REN; $Ps = Ks = 4$ for Shellter.

Overall, REN focused on a restricted solution space, resulting in medium UCD effort and perceived complexity for divergence and convergence (=3). Shellter had productive ideation sessions and worked with a broader solution space, resulting in greater UCD effort and perceived complexity (=4) to arrive at their final solution.

The chosen rubrics and metrics enable a comprehensive assessment, and the spring analogy provides clear guidelines for the instructors, ensuring evaluations are thorough and consistent.

V. CONCLUSION

Design thinking, which starts with understanding end-users' problems, is taught at universities to equip students with the necessary mindsets and skill sets to be innovators and entrepreneurs. Although easy to understand, its implementation is complex. To address this, an operational model of the design thinking process (Fig. 1) was proposed, visualizing the detailed process of any design project. The model (Fig. 1) includes an embedded spring system. Such a system fits well to explain potential variations in the number of UCD methods used (number of coils), size of the knowledge space (coil diameter), difficulty (spring constant), and time transitions (pitch).

The model was illustrated using an 8-week design project with two student projects demonstrating its implementation. The course incorporated various activities addressing the challenges of teaching design thinking, mapping UCD activities (e.g., problem description presentation, user interviews, creative matrix, etc.) to different stages of the model (Fig. 2).

While the case study applied the same UCD methods, individual project variations and outcomes were not captured. Future work should use the model to compare projects with different design processes and evaluate outcomes. The goal is to correlate the model's patterns with design quality, identifying high-quality design processes through standard rubrics. This model can also serve as a process control tool to ensure design quality.

A. Potential Limitations and Adaptability

Limitations of the model include its difficulty to be adaptable to different educational contexts or disciplines, as the specific UCD methods and activities might need modification to fit various fields. In addition, the model's application might be constrained by the resources available in different educational settings. To address these challenges, the model can be adapted and modified to suit diverse educational contexts and disciplines, ensuring its broader applicability.

Finally, incorporating a weighted average rather than the simple average for the different metrics in the spring system could provide a more nuanced assessment, allowing certain parameters to have a greater influence on the overall evaluation based on their importance in specific contexts. This would help refine the evaluation tool's effectiveness in assessing the design thinking process.

B. Implications for Engineering Education

The qualitative findings from the case study demonstrate how the operational model provides a structured approach to teaching design thinking. By capturing the variations in UCD methods and their implementation, the model offers insights into the complexities of the design process. Instructors can use this model to understand better and guide student projects, ensuring that the focus remains on UCD while adapting to the specific needs of their educational context.

This comprehensive approach not only helps in visualizing and assessing the design process but also aids in identifying areas for improvement and innovation in engineering education. The operational model can become a vital tool for fostering creativity, problem-solving skills, and user-centric solutions in engineering students through continuous refinement and adaptation.

C. Future Research Directions

Empirical research is needed to validate the effectiveness of the operational model in improving student learning outcomes. Such research should include diverse projects and educational settings to establish a robust correlation between the model's application and the quality of design outcomes. In addition, addressing biases in the design thinking process is also important. More focus is also needed on fostering critical thinking and ensuring diversity of perspectives within student teams, further enhancing the inclusivity and effectiveness of the design thinking framework.

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REFERENCES

[1] M. Schilling, S. Vicente, T. Johnson, N. Jefferson, and H. Matusovich, "Considering leadership in engineering education: A call to action for research and practice," *J. Eng. Educ.*, vol. 112, no. 1, pp. 18–22, 2023.

[2] T. A. Kelley, *The Art of Innovation: Lessons in Creativity From IDEO, America's Leading Design Firm.* New York, NY, USA: Broadway Business, 2001.

[3] R. L. Martin, *The Design of Business: Why Design Thinking is the Next Competitive Advantage.* Cambridge, U.K.: Harvard Business School Press, 2009.

[4] J. Liedtka, "Innovative ways companies are using design thinking," *Strategic Leadership*, vol. 42, no. 2, pp. 40–45, 2014.

[5] J. Kolko, "Design thinking comes of age," *Harvard Bus. Rev.*, vol. 93, no. 9, pp. 66–71, 2015.

[6] N. Cross, "Designerly ways of knowing: Design discipline versus design science," *Design Issues*, vol. 17, no. 3, pp. 49–55, 2001.

[7] J. P. Guilford, "Creativity: Yesterday, today, and tomorrow," *J. Creative Behav.*, vol. 1, no. 1, pp. 3–14, 1967. [Online]. Available: https://doi.org/10.1002/j.2162-6057.1967.tb00002.x

[8] B. Barbot, R. W. Hass, and R. Reiter-Palmon, "Creativity assessment in psychological research: (Re)setting the standards," *Psychol. Aesthet., Creativity, Arts*, vol. 13, no. 2, pp. 233–240, 2019.

[9] M. Benedek, A. P. Christensen, A. Fink, and R. E. Beaty, "Creativity assessment in neuroscience research," *Psychol. Aesthet., Creativity, Arts*, vol. 13, no. 2, pp. 218–226, 2019.

[10] E. Jauk, "A bio-psycho-behavioral model of creativity," *Current Opin. Behav. Sci.*, vol. 27, pp. 1–6, Jun. 2019.

[11] D. Henriksen, C. Richardson, and R. Mehta, "Design thinking: A creative approach to educational problems of practice," *Think. Skills Creativity*, vol. 26, pp. 140–153, Dec. 2017. [Online]. Available: https://doi.org/10.1016/j.tsc.2017.10.001

[12] L. Lin, R. Shadiev, W.-Y. Hwang, and S. Shena, "From knowledge and skills to digital works: An application of design thinking in the information technology course," *Think. Skills Creativity*, vol. 36, Jun. 2020, Art. no. 100646. [Online]. Available: https://doi.org/10.1016/j.tsc.2020.100646

[13] C. C. Loyola, C. A. Grimberg, and U. B. Colomer, "Early childhood teachers making multiliterate learning environments: The emergence of a spatial design thinking process," *Think. Skills Creativity*, vol. 36, Jun. 2020, Art. no. 100655. [Online]. Available: https://doi.org/10.1016/j.tsc.2020.100655

[14] M.-F. Tsai, "Exploration of students' integrative skills developed in the design thinking of a Psychology course," *Think. Skills Creativity*, vol. 41, Sep. 2021, Art. no. 100893.

[15] V. Yalcin and S. Erden, "The effect of STEM activities prepared according to the design thinking model on preschool children's creativity and problem-solving skills," *Think. Skills Creativity*, vol. 41, Sep. 2021, Art. no. 100864.

[16] H.-C. Kuo, Y.-T. C. Yang, J.-S. Chen, T.-W. Hou, and M.-T. Ho, "The impact of design thinking PBL robot course on college students' learning motivation and creative thinking," *IEEE Trans. Educ.*, vol. 65, no. 2, pp. 124–131, May 2022.

[17] J. A. Leydens and J. Schneider, "Innovations in composition programs that educate engineers: Drivers, opportunities, and challenges," *J. Eng. Educ.*, vol. 98, no. 3, pp. 255–271, 2009.

[18] L. E. Bernold, L. Bingham, P. H. Mcdonald, and T. M. Attia, "Impact of holistic and learning-oriented teaching on academic success," *J. Eng. Educ.*, vol. 89, no. 2, pp. 191–200, 2000.

[19] N. H. Razali, N. N. Nik Ali, S. K. Safiyuddin, and F. Khalid, "Design thinking approaches in education and their challenges: A systematic literature review," *Creat. Educ.*, vol. 43, pp. 2289–2299, Jul. 2022.

[20] J. L. D. Palencia, "Integrating challenge-based learning and design thinking in a course of reaction engines for aerospace," *Int. J. Mech. Eng. Educ.*, vol. 52, no. 2, pp. 123–139, 2024.

[21] A. J. Parmar, "Bridging gaps in engineering education: Design thinking a critical factor for project-based learning," in *Proc. IEEE Integr. STEM Educ. Conf.*, 2014, pp. 1–5.

[22] M. Lammi and K. Becker, "Engineering design thinking," *J. Technol. Educ.*, vol. 24, no. 2, pp. 55–77, 2013.

[23] L. W. Anderson and D. R. Krathwohl, *A Taxonomy for Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives*. New York, NY, USA: Longman, 2001.

[24] B. S. Bloom, *Taxonomy of Educational Objectives*, vol. 1. New York, NY, USA: Longman, 1956, p. 24.

[25] T. K. Holloman, W. C. Lee, J. S. London, C. D. H. Ash, and B. A. Watford, "The assessment cycle: Insights from a systematic literature review on broadening participation in engineering and computer science," *J. Eng. Educ.*, vol. 110, no. 4, pp. 1027–1048, 2021.

[26] V. Kumar, *101 Design Methods: A Structured Approach for Driving Innovation in Your Organization*. Hoboken, NJ, USA: Wiley, 2013.

[27] *Innovating for People: Handbook of Human-Centered Design Methods*, LUMA Institute, Pittsburgh, PA, USA, 2012.

[28] K. Tschimmel, *Evolution 6ˆ2 Booklet*. Matosinhos, Portugal: ESAD, 2014.

[29] A. F. Osborn, *Applied Imagination: Principles and Procedures of Creative Thinking*. New York, NY, USA: Charles Scribner's Sons, 1979.

[30] B. Eberle, *Scamper: Games for Imagination Development*. Waco, TX, USA: Prufrock Press, 1996.