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Connecting design cognition and capstone design education: A proposal

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Abstract
Students are expected to integrate their knowledge and skills in the delivery of capstone design projects. However, such integration is often neither easy nor straightforward. One possible reason is related to the gap between design methods, which can be taught in classes, and design skills, which depend on individual experiences. Research in design cognition provides a descriptive account of the design process and can help us understand how students think during design activities. To leverage the insights of design cognition in education, we first develop the notion of design tasks as a cognitive platform that enables students to connect design goals and approaches with their skills and experiences. These design tasks are categorized into five types: background research, problem framing, idea generation, decision making, and scientific analysis. We argue that these design tasks are applicable across different design stages.

To further integrate the notion of design tasks within the traditional context of design theory and methodology, we propose two theoretical frameworks in this paper. The first is a multi-scale framework based on Activity Theory, incorporating three scales. In relation to design theory and methodology, the macro scale corresponds to design stages, focusing on design goals, while the micro scale describes design actions in delivering projects such as applying design methods. Situated between these, the meso scale uses design tasks mediate between macro-scale design stages and micro-scale design methods. The second framework adopts a dialectical perspective to address the tension between design methodology (normative) and design cognition (descriptive). Here, design tasks serve as a developmental platform, where design methodology provides desirable directions, and design cognition offers insights into students' limitations. Directions for future work in design education practice and research are also discussed.

Keywords: capstone design education; design cognition; multi-scale design framework; design stages and design tasks

1. Introduction

Design cognition is a research field that investigates how designers think in a design process. In contrast to design textbooks that tend to prescribe how students *should* design, the research of design cognition offers observational studies and develops models to describe human-centered design processes. Common topics of design cognition include design fixation [1-7], problem-solution co-evolution [8-11], and design metacognition [12].

As a capstone course instructor, the results of design cognition are interesting because they can explain why students think or behave in certain ways in capstone projects. For example, the phenomenon of problem-solution co-evolution tells us that it is common for designers to use tentative design solutions to improve their understanding of design problems. With this idea, we may not insist on having a "perfect" problem statement from a design team before they can start proposing design solutions.

Also, design cognition helps us understand the gap between design methods and design practice. From our teaching experience, even though design methods were taught in the class, students may not have adequate skills and experience to apply these methods meaningfully for their capstone projects. This motivates us to reconsider the teaching of capstone courses from the "design methods" aspect to the "design cognition" aspect. For example, students are not restricted to apply certain methods or procedures (e.g., developing three design concepts and using a decision matrix for concept selection). Instead, they are required to report their individual contributions with respect to certain types of *design tasks*. This approach allows more flexibility for students to utilize their knowledge and experience to complete the design tasks. We, as instructors, can observe authentic design thinking from students and offer more direct guidance to improve their design thinking skills.

From the teaching of design methods to the emphasis of design tasks, it can be considered a process of Reflective Teaching [13-14]. Yet, to effectively improve our design education practice, we also want to start the journey from Reflective Teaching towards the Scholarship of Teaching and Learning (SoTL) [15-18]. The purpose of this paper is to reflect on our current capstone teaching practice and propose preliminary theoretical frameworks to integrate the aspects of design methods and design cognition for design education. We believe that this theoretical proposal can support our future SoTL activities.

In Section 2 of the paper, we will discuss how we teach capstone courses from the design cognition aspect with some reflective notes. Then, we will offer two theoretical frameworks in Sections 3 and 4 that integrate the notion of design tasks in the traditional context of design theory and methodology. Section 5 will discuss our plan to extend the current work for design education practice and research in the future. Section 6 will conclude this paper.

2. Capstone design teaching: practice and reflection

When the primary author of this paper started to teach capstone courses in 2014, design theory and methodology were used as the key content to guide students with their capstone projects [19-22]. However, after various attempts and adjustments over the years (e.g., having an exam on design methods and conducting design workshops), we still do not find strong correlation between the learning of design methods and the quality of design work in capstone projects. For example, students can use the decision matrix flawlessly according to a textbook, but the justification of the selected design concept can still be weak or inappropriate.

As one reflection, the teaching approach using design theory and methodology implies an "applied science" philosophy that students need to learn theories and principles first before they can apply them for real problems. Another implication is that the same principle or method can be "simply applied" to different problems, regardless of who the designers are (e.g., junior or experienced). However, for students, "applying theories" meaningfully in design projects is not always straightforward, as they may find it easier in other technical engineering courses.

As a result, we decided to discontinue teaching design methods as mandatory content in capstone design courses. Instead, we took on the project manager role by defining expectations and tracking the progress of individual projects. By guiding and observing how students develop design solutions, we started to notice some patterns of student thinking in design. Gradually, we developed a pedagogical approach that emphasizes the execution of design tasks as individual contributions to the team projects.

In a nutshell, the pedagogical approach describes engineering design as a three-stage process, and each stage is elaborated as follows.

- ❖ Stage 1: Conceptual design. The purpose of this stage is to understand the given design problems and recognize the available project time and resources. The outcomes include refined problem statements and proposed design solution(s).
- ❖ Stage 2: Design development. The purpose of this stage is to develop and analyze the details of the proposed design solution.
- ❖ Stage 3: Design verification. The purpose of this stage is to provide and analyze the evidence concerning the performance of the proposed design solution.

While the articulation of design stages is common in design textbooks, we want to highlight two features of this three-stage process observed from our practice. First, the requirement of "design verification" can help students develop critical thinking in design. For example, instead of treating the completion of prototypes as the final milestone of capstone projects, students need to put time and resources to reasonably test their prototypes and reflect on the quality of their design solutions. Second, as we limit the number of design stages to three, the same design process can be flexibly applied to a wide range of design topics (e.g., aerospace projects, sustainability projects).

Yet, we want to note that these design stages are defined at their most general levels, and they are open to further refinements for design learning. For example, the conceptual design stage can be divided into problem definition and concept generation / selection [19-21], and the design development stage can be divided into embodiment / preliminary design and detailed design [19-20]. As our capstone course involves multidisciplinary projects with diverse topics, we keep these three design stages to match most of the design experiences from students.

Then, for each design stage, we guide students that there can be five types of design tasks, which are briefly described as follows.

- ❖ #1: Background research. Identify the unknown information for the projects and learn new materials from valid sources.
- ❖ #2: Problem framing. Define the scopes of different problems and plan for the solution approaches.
- ❖ #3: Idea generation. Develop possible solutions for different problems and create new design content and details.
- ❖ #4: Decision making. Identify viable options and decision criteria, conduct trade-off analysis, and justify the final choice.

- #5: Scientific analysis. Use engineering and scientific knowledge to develop design details and analyze the designed objects or systems.

Interestingly, when we take the “design tasks” (instead of design methods) as the instructional and guiding approach, our discussions of the design projects with students can become more “natural”. For example, we can first learn how a team thinks in their concept selection process and then point out any overlooked aspect without the necessity to discuss the proper application of decision matrices for the “winner” design. We have also developed a rubric to describe three assessment levels of thinking (i.e., superficial, procedural, and deep), as outlined in Table 1, for these design tasks.

Despite the observed benefits, there are also challenges. First, as students are mostly occupied by the technical details of their capstone design projects, we can only teach the concepts of three design stages and five types of design tasks briefly. Second, we need to oversee more than 20 projects (with more than 120 students), we need to rely on academic advisors to evaluate the projects’ details. However, academic advisors often use their own standards in project evaluation, where it is difficult to introduce “design tasks” as another observational and assessment aspect.[1] These challenges motivate us to extend the idea of “design tasks” from reflective teaching to the direction of Scholarship of Teaching and Learning (SoTL). In the next section, we will discuss a framework that integrates design tasks in the traditional content of engineering design.

Table 1. Three assessment levels for design tasks

	Superficial thinking	Procedural thinking	Deep thinking
Background research	Recognize only the knowledge learned before	Know how to search external information	Filter the relevant information for the design problem.
Problem framing	Frame design problem as school exercises that were taken before	Define design problem based on my best skills to show	Convert vague information to design tasks with estimation of workloads
Idea generation	Ideas may be logical but not practical to the design problem	Adopt ideas that are closest to the team’s experience	Develop ideas based on the project’s need and constraints
Decision making	Show the knowledge of using decision matrix	Discuss the trade-off between different options	Recognize limitations and make authentic decisions
Scientific analysis	Cite equations that were learned before	Anticipate results from the analysis and check their relevance to the design problem	Apply scientific principles for modelling and analysis specific to the design problem

[1] To clarify, all academic advisors use the same marking rubrics to maintain a certain level of consistency in grading, where they will evaluate design quality, academic quality, and communications. Yet, we have not enforced academic advisors to use “design tasks” as an evaluation angle. This will be a future work to be discussed in Section 5.1.

3. Design tasks in a multi-scale framework

The traditional content of engineering design for teaching has two features. First, it describes engineering design as a multi-stage process. Second, it provides procedures or design methods to help students develop design solutions and details for each design stage (e.g., [21-22]). With these two features, this section seeks for a theoretical framework that can integrate the notion of design tasks in the traditional teaching of engineering design.

To propose a theoretical framework, we adopt the multi-scale framework from [23], which has a theoretical ground in Activity Theory [24-26]. The framework in [23] suggested a three-level decomposition of design work as: activities → tasks → actions. Then, they proposed a framework of multi-scale design processes, i.e., macro-scale, meso-scale, and micro-scale, to map the work sequences of activities, tasks, and actions, respectively.

Figure 1 illustrates the integration of our theoretical framework with the multi-scale design processes by [23]. The traditional content of engineering design is mapped to the macro and micro scales to represent the design stages and the design methods, respectively. The new construct of design tasks is positioned at the middle meso-scale, which mediates the connection between design stages and design methods.

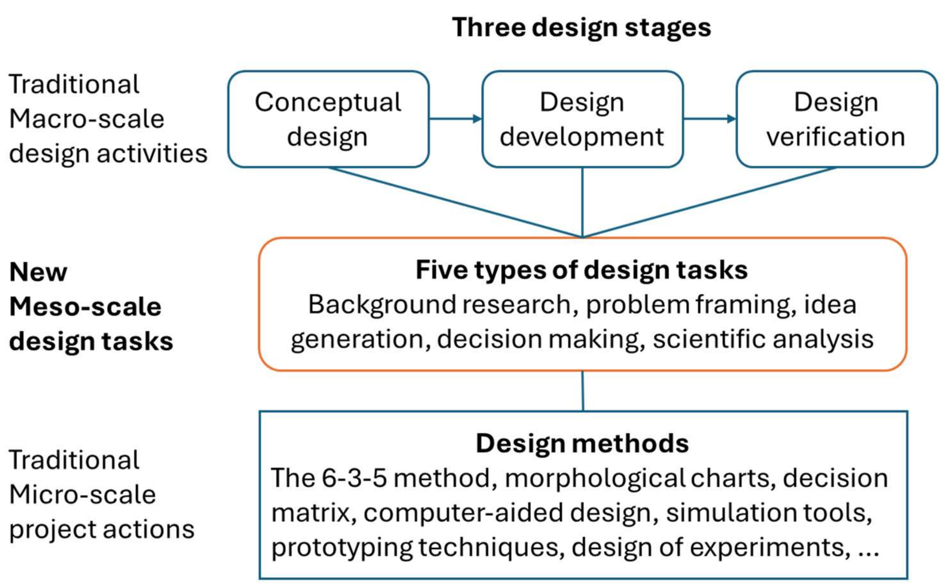

Figure 1. Multi-scale design framework

3.1. Macro-scale design activities

According to [24], the notion of "activity" can be interpreted as "a goal directed system, where cognition, behaviour, and motivation are integrated and organized by the mechanism of self-regulation toward achieving a conscious goal" (p. 138). As "goal" is a key feature to interpret the notion of “activity”, goals can be interpreted as common expectations between students and instructors. In particular, we can suggest three design stages as design activities with their goals as follows.

- ❖ Activity 1: Conceptual design → Goal: Propose a tentative design solution
- ❖ Activity 2: Design development → Goal: Develop the details of the proposed design solution
- ❖ Activity 3: Design verification → Goal: Examine the performance of the design solution

From our experience, while the activities of conceptual design and design development are obvious for students, design verification is not always recognized as one important activity. Since we emphasize design verification as one important design stage, we notice that students can develop more critical thinking for their design work. This illustrates how the setup of design activities can impact the learning outcomes of students.

In design education, it is common for instructors to observe “what students do” to guide and assess their design work. In our theoretical framework, we classify “what students do” to the micro-scale project actions, which will be discussed next.

3.2. Micro-scale project actions

In our context, micro-scale project actions can be interpreted as observable design work conducted by students. This conception of actions is aligned with the definitions as “discrete parts of a task” [23, p. 4] or “concrete element of activity” [25, p. 132]. Applications of design methods can be considered as project actions.

As discussed in [23], it is often observed that macro and micro-scale processes are connected “via logical argument” (p. 6). For example, it is logical for a design team to use a decision matrix to compare two competing concepts in conceptual design. However, when such logic becomes part of the course instructions, students would take such logic as rules, which must be applied in the projects. In fact, the transition from design goals (e.g., select a good design concept) to appropriate project actions is not as straightforward as logical links, where the experience and abilities of designers are important to make meaningful transition. In other words, when students jump directly from the macro-scale goals to the micro-scale actions, the space for students in design thinking could be diminished. This may justify why we may need the meso-scale level from the educational viewpoint.

3.3. Meso-scale design tasks

Bedny and Harris [25] referenced the notion of tasks as “some situation requiring achievement of a goal under specific condition” (p. 135). In our framework, we can classify five types of design tasks at the meso-scale. To illustrate, let us interpret the activity of “design verification” as one goal for a capstone project. Then, design tasks can be interpreted as “some situation requiring achievement” of this goal. For example, the task “idea generation” describes a situation that the student team is expected to develop ideas for design verification. This situation may lead to some questions for the student team such as:

- ❖ How many ways can the team consider testing or verifying the proposed design solution?
- ❖ Can the team have the resources to conduct one type of design testing?
- ❖ What kind of test results does the team want to show (related to the team's values and preferences)?

These questions may speak for the notion of "under specific condition" cited above, where student teams create their own condition in project delivery. In this view, design tasks at the meso-scale are intended to guide students to think of some typical aspects to achieve the goals at different design stages. This also echoes the note by [23] that the intent of the meso-scale design tasks is to accommodate "a wide array of perspectives" (p. 6). In addition, their study has classified "ideation" and "information seeking" (p. 17) as codes for meso-scale tasks, which can be interpreted as "idea generation" and "background research" in our framework. This supports our idea of classifying design tasks at the meso-scale that mediates macro-scale design stages and micro-scale project actions.

As a closing remark, the involvement of "design tasks" at the meso-scale is not about giving up the application of design methods for capstone projects. Instead, design tasks can be used as a cognitive platform for students to apply their experience and knowledge. When conducting design tasks, students are asked to choose and apply design methods and engineering knowledge based on their current understanding and skills. As instructors, we can observe and guide students for their design processes based on what they are capable to do. This leads to a developmental aspect for students to learn design skills.

4. Developmental aspect in engineering design education

As previously also mentioned, design methods and design cognition demonstrate two different aspects in design education. Design methods represent a normative design aspect, which tells us how design work should be done, while design cognition investigates how people solve design problems, providing a descriptive aspect of design processes. Though these two aspects are not contradictory, they may present some tension for design education.

For example, the results of problem-solution co-evolution implicate that students can understand the design problem better by tentatively jumping to a solution since a tentative solution can provide them some concrete and tangible information of the problem's situation. However, "jumping to a solution" could be considered an undisciplined design practice since the design team should refine the problem statement before generating design solutions. In this example, the tension for design education is whether we should advice the design team to "jump to a tentative solution" to better understand the problem or not.

To address this tension, we can consider dialectic as one theoretical lens for a resolution, where contradiction can drive the restructuring of relationships for positive constructions [27]. In the context of design education, while the aspect of normative design can be directional and aspirational to the desirable states of design processes, the aspect of descriptive design can guide instructors to understand how learners think in a design process. Both aspects can collaboratively offer a developmental framework, that allows instructors to guide students in developing their design skills. In our approach, we recognize that meso-scale design tasks are suitable for us to expand the developmental aspect for design education. Table 2 summarizes the normative, descriptive, and developmental aspects for five types of design tasks. This section will elaborate the content of this table.

Table 2. Different aspects of design tasks

	Normative	Descriptive	Developmental
Background research	How to find and discern creditable information	Sensemaking and framing	Indicate directions of information search to extend one's experience
Problem framing	How to compare and write problem statements	Problem-solution co-evolution	Allow the use of design solutions to frame design problems
Idea generation	How to generate design concepts with methods and procedures	Design fixation	Use "concrete anchors" to develop critical mind in generating ideas
Decision making	How to select the best option using criteria and methods systematically	Recognition-primed decision making	Emphasize the understanding of the selected choice(s)
Scientific analysis	How to apply science knowledge for design problems	Mental models and simulation	Use scientific concepts to describe the design problems and solutions

4.1. Background research

From the normative aspect of background research, we may teach students the techniques for information searching and the discernment of information creditability (e.g., [28, pp. 109-111]). From the descriptive aspect, two constructs of cognition can be relevant to design: sensemaking and framing. Sensemaking can be interpreted as a cognitive process, where a person aims to construct their own understanding of a problem or a phenomenon using their experience and knowledge [29-30]. In the research of cognition and sensemaking, researchers have formulated a concept called "frame" to model the mental structure used by a sense-maker [31].

Let us use the Data/Frame (DF) model developed by [32] to illustrate how sensemaking and framing are relevant to background research. In a nutshell, the DF model describes how sense-makers tend to preserve and (slightly) elaborate their own frames when they solve new (design) problems. When "typical" frames are not sufficient to address the new problems, reframing is required, where a new direction for background research would be needed. One message of the DF model is that sense-makers have a strong tendency to keep their "old" frames to understand the problems, where it requires conscious reflections and probably interventions to make reframing happen.

Using the DF model, one background research skill for students to learn can be the ability to select and learn new content to support frame elaboration and reframing rather than recalling learned materials to preserve their existing frames. Three possible directions for background research can be considered as follows.

- ❖ Preserve the frame. Review the theoretical content of previous courses and aim to apply the theories to guide the design processes.
- ❖ Elaborate the frame. Study and analyze existing products for design inspiration.
- ❖ Reframe. Study the motivations and the context of the design problem to explore design solutions from different angles.

We should note that these background research directions are not mutually exclusive, and they can all be conducted and shared by the same design team. Yet, these three directions illustrate different possibilities for a design team to do background research. For example, if the team only takes the "preserve the frame" direction, they may reinvent the wheels (as they may not be aware of existing designs) and find it difficult to justify their design's novelty. In contrast, in the "reframe" direction, the design team needs to be open to the problem's context and to any new design requirements that may not be recognized in the original problem statement.

From the developmental aspect, the information search and checking skills alone are not sufficient because they do not specify the search directions. The descriptive aspect as the DF model implies that designers have a strong tendency to reuse their "old" frames for sensemaking. Then, one developmental approach is to help the design team see the possible "reframing" direction that is specific to their problem's context.

4.2. Problem framing

Problem statements are narratives that help designers to frame and define the scopes of design problems. From the normative aspect, the importance of problem statements is often emphasized since weak design results can often be attributed to any misunderstanding of design problems and inappropriate problem statements (e.g., [20, pp. 16-19]). Consequently, an analysis was conducted to compare the attributes of good and weak problem statements (e.g., specific design purposes, free from biased design solutions) (e.g., [20, pp. 43-46]). It often leaves an impression that the design team should not start exploring design solutions without having a good problem statement.

From the descriptive aspect, the literature of sensemaking and framing discussed earlier is also relevant to problem framing as these cognitive processes describe how a person understands design problems, and such understanding helps the person to define the problem's scope and formulate the design tasks. Another relevant design cognition phenomenon is problem-solving co-evolution (PSCE). From the research of PSCE, it is observed that designers often use tentative design solutions to refine their understanding of the design problems [10].

Here we can imagine how PSCE can be relevant to design instructions. While our instructions can still tell the capstone team to define their problem statement with specific design goals and requirements, we can also ask them to promptly suggest tentative design solutions and discuss their pros and cons. This exercise may help them recognize more contextual details of the problem and technical feasibility of certain design ideas. In view of PSCE, this recognition can support the design team to refine the problem statements.

From the developmental aspect, if it is quite normal for a designer to use tentative design solutions to (re)frame the design problems, we may not need to insist to have the "perfect" problem statement before exploring design solutions. Instead, we can be more sensitive to the team's ability in problem framing. If the team cannot readily define and frame the design problem, we can encourage the team to form conceptual design solutions, which can be used to examine how much they understand the original design problem. At the same time, PSCE should not be taken as an excuse for careless design thinking, where the design team just moves to a design solution without considering the design needs and constraints. In contrast, PSCE should promote flexible design thinking, where the design team is encouraged to use different resources (including tentative design solutions) to improve their problem framing skills.

4.3. Idea generation

Design methods for idea or concept generation are abundant in design textbooks such as brainstorming techniques (e.g., 6-3-5 method) and morphological charts. However, in the capstone design context, we do not often observe that student teams would use these methods effectively and meaningfully to generate design ideas. In contrast, the literature of design fixation shows that designers can be easily fixated to specific examples or ideas when generating new design solutions [1-2].

However, we can also interpret the observations from the design fixation literature that designers tend to use concrete examples or "anchors" to help them develop design solutions. From our capstone teaching experience, we also notice that students cannot easily use the abstract notion such as "function" to generate multiple design concepts with morphological charts. Our explanation to this difficulty is that students' cognition has already been occupied by the details of unfamiliar design problems. Then, students do not have sufficient cognitive resources, or simply design experience, to take the abstract angle to explore possible design solutions.

From our developmental aspect, the design instruction should not aim to avoid design fixation completely, as it would be difficult for novice designers anyway. Instead, we should help them discern the quality of fixated ideas. For example, if a team is fixated to a poor idea, we do not ask them immediately to apply concept generation methods to get more innovative ideas. Instead, we can tentatively go with the poor idea and ask the team how the idea could be further developed and tested. In the discussion, the team may recognize the weakness of their fixated idea and get clearer ideas of how a good design solution may look like. To novice designers, it seems to be a workable path to learn critical thinking in idea generation.

4.4. Decision making

Decision theory is a vast field, and decision methods from this field have been adapted for concept selection (e.g., decision matrix and analytic hierarchy process) [19, 33-34]. As one typical instruction for capstone projects, we may ask the teams to generate at least three different design concepts and apply a decision method to determine the "winner" design. From our capstone teaching experience, design teams under this instruction may "make up" three design concepts, as they already know which concept is the "winner" design before applying decision methods. To fulfill the instructional requirement, they still run a decision matrix to "prove" the winner design. From a pedagogical view, one drawback of this situation is that students treat decision making as a matter of executing a procedure. They may miss the chance to use decision making as a thinking process to gain more understanding of their design solutions.

One feature of decision methods is an explicit comparison of fixed options on the table. The work of recognition-primed decision making tries to show that such explicit comparison is not the only approach for experts to make decisions [35-36]. Instead, experts often recognize the possible options from their experience and use mental simulation to "prime" the final decision. This work highlights one issue that design options are not often fixed as competing products in the market. Decision making can be a process to refine the design ideas, and the result of this process will become the final design solution.

If we see recognition-primed decision making as a valid process for students in a capstone project, we do not need to require the design teams to execute the process of "three design options → decision method". Instead, if the design team is keen on a specific design solution, we can ask the team how they can evaluate their solution and compare it with other similar ideas. If the team already has multiple design options on the table, instead of asking for the "winner", we can ask the team to describe the trade-off between design options. Emphasizing the evaluation and trade-off aspects in decision making can help students to understand their design options better, which is important for future design development and communication.

4.5. Scientific analysis

Though the importance of scientific knowledge in engineering education is clear, the relationship between scientific knowledge and engineering design is not entirely obvious for instructors and students. One classical view is the “applied” relationship [37], where scientific knowledge is applied to develop design solutions. To students, the “applied” relationship may implicate that the correct application of scientific knowledge can lead to good design results. Consequently, some students choose to focus on demonstrating their scientific knowledge in a design project with less critical thinking of its relevance to the design solutions.

For example, as one common observation, students like to use finite element analysis (FEA) and computational fluid dynamics (CFD) tools in their capstone projects. Then, they tend to present the FEA and CFD results as “proofs” in their design projects. For example, they may assert that the design solution is safe because the maximum stress shown in the FEA result is less than the strength of the material. However, it is less common for them to justify the settings of boundary conditions (e.g., do the boundary conditions represent the worst-case scenarios?) and discuss some design factors that could not be analyzed in FEA. In other words, sometimes it is not obvious for students to interpret scientific analysis results appropriately in the design context.

In contrast to the “applied” relationship, another possible relationship is “modeling”, where the role of scientific knowledge is to model and describe the target systems using scientific concepts and formulations. The “modeling” relationship suggests us to observe how capable of students to use scientific knowledge as a language tool to describe the properties and mentally simulate the behaviours of design solutions. In science education, researchers have coined the term “mental models” to describe how experts use scientific concepts to mentally simulate and make sense of natural phenomena [38-41].

In our consideration, the “modeling” relationship is more appropriate for design education since the construction of mental models allows designers to integrate scientific knowledge in the design context. For example, when we perceive FEA as a modeling tool, we would be interested in the assumptions behind how FEA is applied in the design context (e.g., the settings of boundary conditions). When students need to justify the assumptions, they would engage some forms of mental simulation to find the connections between scientific knowledge and design solutions. The recognition and learning of such connections can enrich students’ understanding of their design solutions.

As a closing remark, how students learn design skills cannot be independent from their own knowledge and personal experience. While the normative aspect of design can inform how good design practices may look like, the descriptive aspect of design can explain how people tend to think in design processes. In design education, we should consider both aspects to develop the developmental aspect that allows time and space for students to develop their design skills. The next section will discuss our future directions to develop this aspect.

5. Directions for the future work

5.1. Education practice – design spine

The purpose of a design spine is to offer a scaffolding structure for students to develop design skills progressively in their four-year engineering programs. Regarding design skills, we refer them to as the ability to deliver five types of design tasks in different design stages. To propose a design spine, we have two assumptions. First, if students can execute one type of design tasks well (e.g., background research) for one design stage (e.g., design verification), they can transfer the relevant skills to other design stages. Second, students can learn design skills better through concrete information (in contrast to abstract concepts). However, early design stages are often vague and abstract. Thus, we advocate that students can start learning the later design stages with five types of design tasks. Towards the upper years, students can move to the learning of the earlier design stages.

In their first year, students take a common introductory course that aims to provide hands-on design experience with pre-defined design themes (e.g., design a product using the Arduino platform to help a specific group of users). In addition to some typical design learning such as basic design methods, communication and teamwork, students can learn the design framework discussed in Section 2. One exercise for students is to describe their hands-on projects using the framework's terminologies (e.g., design stages and design tasks), which can help them regulate their design thinking and organize design processes. This can be considered as a kind of metacognition training, where students can reflect on their own thinking in design processes.

When students are enrolled to a specific engineering discipline starting from the second year, the domain knowledge can also be integrated for the development of design skills. Let us take Sustainable Systems Engineering discipline as an example. In addition to the common knowledge base (e.g., mechanics, thermodynamics, control), systems thinking, sustainability and design justice considerations are particularly emphasized in the program (one such approach is life-cycle analysis). To illustrate our proposal, the design of an autonomous snow removal device is used as a hypothetical design project.

In the second year, the learning objective can focus on the last design stage, design verification, which is more concrete for students and can help them develop critical thinking for future design work. As one project suggestion, we can provide the existing snow removal products and ask students to evaluate these products objectively. Note that it can be an open-ended, hands-on problem, where students would need to engage different design tasks such as:

- ❖ Background research: Study the specifications and the working principles of the given snow removal products.
- ❖ Problem framing: Identify the possible performance measures and the resources for design verification (e.g., instrumentation tools).
- ❖ Idea generation: Design experiments to collect data for performance measures.
- ❖ Decision making: Select the key performance measure(s) given the time constraint.

- ❖ Scientific analysis: Conduct the life-cycle analysis (e.g., compare products powered by gas versus electricity).

In the third year, the learning objective can focus on design development, while students can bring in their prior design verification experience for the design projects. For example, a project can ask students to design a manual snow thrower that can pick up and throw snow to one side. In this context, five types of design tasks can be involved such as:

- ❖ Background research: Learn existing snow throwers and try to understand why the manual snow throwers are not common.
- ❖ Problem framing: Define a realistic scope of development, knowing that design verification can take time and effort.
- ❖ Idea generation: Modify the geometric details of a small electrical snow thrower for manual operations.
- ❖ Decision making: Compare two designs of handles in view of human factors
- ❖ Scientific analysis: Estimate the minimum (or theoretical) force required to “throw” snow.

In their capstone design year, while students are expected to work on unique design projects (e.g., it will not be the snow removal devices), they can potentially transfer their prior learning experience and cognitive skills to new design contexts. Listed below are examples of cognitive skills associated with design tasks that can be transferred to capstone design projects.

- ❖ Background research: Recognize the importance of understanding existing designs and products for new development.
- ❖ Problem framing: Estimate the effort of design development and verification for the overall scheduling of a capstone project.
- ❖ Idea generation: Understand and prepare for the gap between paper design and real-life design.
- ❖ Decision making: Understand why justification of a design choice is more important than the application of a decision matrix.
- ❖ Scientific analysis: Recognize how the analysis results should be used to inform design processes and decisions.

Though design evaluations based on the delivery of design tasks are possible (e.g., Table 1), the evaluations of capstone projects in our case could involve different types of stakeholders (e.g., instructors, academic advisors, and industry sponsors), who may just want to evaluate design projects in view of some “common-sense” aspects such as design quality and academic quality. Thus, our current plan is to evaluate student performance in design tasks in their pre-capstone design courses, where course activities can be designed specifically for the learning of design tasks. We expect that students can have honed their cognitive skills related to design tasks when they work on capstone projects, which quality can be assessed by general professionals without an explicit breakdown of design tasks.

5.2. Research questions for future research

With the advocation of cognitive design skills for design education, a general research direction is to investigate how students think when doing design projects. In the development of research methods, we can consider the application of cognitive task analysis [42] and develop tools to assess cognitive design skills (e.g., three assessment levels in Table 1 are one idea). Then, we can consider the following research questions (RQ):

- RQ 1: What can be observable information from students to examine their cognitive design skills? The answers to this question can help us develop rubrics for design education and assessment tools for research.
- RQ 2: What is the correlation between the quality of cognitive design skills and the quality of design solutions? This research will investigate whether the training of cognitive design skills can improve students' engineering design skills in general.
- RQ 3: Can students progressively improve their cognitive design skills through training (or are cognitive design skills similar to personal traits that cannot be effectively trained)? This research will investigate the efficacy of the training materials for cognitive design skills.
- RQ 4: Can cognitive design skills (e.g., background research) be transferred among design stages? For example, if a student is good at background research for design verification, can such good background research skill be readily applied in the stage of conceptual design? This research will investigate whether the training of cognitive design skills can develop transferable design skills.

6. Closing remarks

While design textbooks and design methods may present a prescriptive account for design education (e.g., how students *should* design), the aspect of design cognition can help us understand how and why novice designers conduct their design projects in certain ways. In this paper, we first discuss our pedagogical approach by defining five types of design tasks that students can work on for their capstone design projects. Then, we explore two theoretical frameworks based on Activity Theory and dialectic to present a possible integration of design methods and design tasks for design education. A key message is that design tasks can be a cognitive platform for students to develop design skills according to their experience and knowledge. Based the theoretical frameworks, we propose and discuss our future work toward the education practice of design spine and the research questions to understand the relationships between design tasks and cognitive design skills.

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