Transdisciplinary Engineering Design Process: Tracing Design Similarities through Comparison of Design Stages across Engineering Disciplines

Introduction

The integration of technology into contemporary product development practices has transformed the engineering design process from disciplinary [1-3] to transdisciplinary. This integration requires discipline experts to share technologies and knowledge beyond their traditional boundaries to design and create an artifact, thus resulting in a transdisciplinary design process. A transdisciplinary design process is a problem-solving activity that brings together, scientific knowledge and problem-solving techniques from multiple disciplines to solve a complex problem [4]. A significant number of industrial studies traced the design process commonalities between engineering disciplines across a broad spectrum of industries [5-7]. These studies identified a six-stage transdisciplinary design process, which is widely accepted and applicable across engineering disciplines. The six stages are Planning, Concept Development, System-Level Design, Detail Design, Implementation and Testing, and Production. In light of current transdisciplinary design practices in the industry, Ertas [8] identifies challenges currently faced by engineering education and suggests responding to these changes by introducing transdisciplinary engineering design education.

This paper is part of an empirical research project carried out at the Engineering Faculty at the University of Alberta. The project entitled Transdisciplinary Design Education for Engineering Undergraduates focuses on the transdisciplinary engineering design processes with an aim to introduce a common understanding of transdisciplinary design to the first-year engineering undergraduates [9]. This common design understanding is necessary to overcome disciplinary barriers such as discipline-specific tools, methodologies, and terminologies. This can be done by identifying common design stages and common design concepts across engineering disciplines [10]. The paper discusses a part of empirical research that was carried out to collect discipline-specific engineering design processes from multiple disciplines, identify the similarities between their design stages, and propose the six-stage design process as a common transdisciplinary engineering design process. The understanding of design commonalities between academic engineering disciplines is based on the earlier results obtained [11-13], which revealed a “shared understanding of design” between multiple engineering disciplines in the industry. These findings are summarized in the section below.

Literature Review on Engineering Design Process

An engineering design process is can be defined as a step-wise iterative approach to create an artifact [11]. This step-wise approach is often represented using a design process model. A design process model consists of common structural components, also called “patterns of design”, which comprise of *design stages, design activities* and *execution strategies* [11-14].

A *design stage* is defined as a period of time after which a product changes its state [12]. A design process is divided into several design stages where each design stage consists of multiple design activities. An *activity* is defined as a problem-solving process that involves a sequential series of actions. The activities are carried out to fulfill the fine details of a design stage and are iterative in nature. Finally, an *execution strategy* is defined as the approach taken to execute the activities throughout a design process.

Despite the structural similarities, design processes remain largely mono-disciplinary due to the functional and contextual differences in the product [11,15]. A reflection of typical design stages from various disciplines can be seen in [3,16-23]. Many authors argue that, due to the varying contextual nature of the products across disciplines, it is difficult to agree that there exists a common design process.

However, earlier industrial studies carried out have demonstrated that disciplinary experts demonstrate similar understandings of the engineering design process. A study performed by Gericke and Blessing [13] reviewed 64 design process models across 9 engineering disciplines and proposed the following set of most common transdisciplinary design stages: *Establishing A Need; Analysis of Task; Conceptual Design; Embodiment Design; Detailed Design; Implementation; Use; and Closeout*. Gericke et al. [7] conducted interviews with 23 industrial professionals and measured the applicability of similar design stages. Qureshi et al. [5,6] also conducted similar empirical studies with industry professionals from multiple disciplines and found a common understanding of the design stages among the discipline experts.

Methods

The study consisted of 34 semi-formal individual interviews with engineering design professors and academic leadership representatives in the Faculty of Engineering. The interviews were carried out with design experts from eight engineering disciplines in the Faculty of Engineering, namely Mechanical, Chemical, Civil, Mining, Petroleum, Materials, Electrical, and Computer Engineering. Each interview consisted of three sequential sections: 1) a written questionnaire; 2) open-ended questions; and 3) a cognitive game task. This paper presents the analysis of results obtained from participants in the second and third sections of the interviews.

The interviews were conducted to understand the discipline-specific engineering design processes and their stages to identify whether or not a generic design process can be utilized to represent design processes across disciplines. This common engineering design process would then serve as a basis to measure the similarities between design stages across disciplines. The results from the interviews were analyzed to test the following hypothesis: "*The stages of engineering design processes are conceptually similar across the engineering disciplines, regardless of the terminologies used to name them*."

The hypothesis was tested to identify only the conceptual similarities between the design stages instead of linguistic to preserve the disciplinary terminology of each process. In order to carry out the study, it was important to find a baseline generic engineering design process as a reference. For this purpose, several design processes were considered [17,20-22]. However, based on the existing literature and current teaching practices at the University, the six-stage engineering design process described by Ulrich and Eppinger [16] was considered as a reference. The six-stages of the design process are *Planning, Concept Development, System-Level Design, Detailed Design, Implementation and Testing, and Production*.

Participants

The participants consisted of 34 engineering design professors from the Faculty of Engineering at the University of Alberta. The interviews were one hour long and carried out in person. Participants were selected from the pool of professors who teach courses with significant engineering design content according to the Canadian Engineering Accreditation Board (CEAB) regulations [24]. 46 courses were identified as core design courses. Out of these 46 courses, 23 were selected for this study. The professors belonged to 4 engineering departments, consisting of 8 engineering disciplines. As shown in Table 1, out of 34 participants, 30 professors were involved in teaching design courses to undergraduate students. There were 6 academic leadership representatives, including associate deans and departmental chairs, 4 of whom did not teach any design course but were interviewed to conduct other parts of the study.

Table 1. Participants' distribution across the engineering disciplines.

Department	Discipline	Professors
Mechanical Engineering	Mechanical Engineering	13
Chemical engineering	Chemical Engineering	3
	Materials Engineering	5
Civil engineering	Petroleum Engineering	1
	Civil Engineering	3
	Mining Engineering	2
Electrical engineering	Electrical Engineering	6
	Computer Engineering	1
Total		**34**

Interviews

Before the start of the interview, each participant was briefly introduced to the project, its goals, and the interview process. Before the start of the interview series, 5 pilot interviews were conducted to perform any necessary changes in the questionnaire. Two research assistants conducted the interviews. Each interview started with a written questionnaire that was designed to collect basic information about the participant's design experience and the course taught by them. The results of the written questionnaire are out of the scope of this paper and therefore not discussed. The data for the current study is taken from the second and third section of the interviews i.e., an open-ended questions section and a cognitive game task, which were designed to collect information about engineering design processes and their stages, as described by the participants. The section below describes the details of the interviews and the data obtained from them.

The Open-Ended Questions Section

This section was designed to collect the descriptions of the discipline-specific engineering design processes and their design stages. It was supported by additional questions on engineering design processes and description of discipline-specific products. The participants were asked whether they follow a methodological design process for teaching design, and if so – to name that process as well as its design stages. The design process described by each participant was discipline-specific. The participants were then asked to describe their discipline-specific design stages based on the following questions:

1. *Can you define the design process/method as per your course? How many stages does it have? Can you name the design stages in it?*
2. *Is there an iteration within and/across the design stages?*

If participants answered *yes* to the second question, they were asked if there was an overlap or some iterations between and within the stages. This part of the open-ended questions section was excluded for the 4 participants who do not teach any design course. In order to map the discipline-specific design processes on the generic design process, participants were also given a cognitive game task.

The Cognitive Game Task

The cognitive game task, based on Bloom's Taxonomy [25] and combined with the proposed six-stage engineering design process [16], was designed to determine a normalized six-stage design process from each discipline. Participants were asked to map disciplinary engineering design stages on a proposed transdisciplinary engineering design process. Each participant was given a generic six-stage engineering design process consisting of the following stages: *Planning (PL), Concept Development (CD), System-Level Design (SLD), Detail Design (DD), Implementation and Testing (IT),* and *Production (PR).* In the first step of the game, all participants were given an option to rename and reorder the design stages according to their disciplines. As a result of this activity, participants successfully obtained a six-stage mapped design process that was unique to their own discipline but also generic enough to describe the design stages at an abstract level. The other activities performed by the participants during the cognitive game task and their results are describes and presented in [10,26,27].

Results and Discussions

The data obtained from Sections 2 and 3 of the interviews generated the pre-game and post-game design stages, respectively. These design stages were analyzed and compared thereafter. The results are described in the following sections.

Pre-Game Design Stages

The design stages obtained from participants as a result of open-ended design process description questions were named as pre-game design stages, and the processes were called pre-game design processes. Table 2 shows the data of 30 participants who teach design through standard, formal or informal design methods/design stages. The 4 academic leadership representatives who did not teach any course were not asked to describe design stages at this point.

Column 2 of Table 2 shows the number of participants who use a standard design method to teach engineering design. These methods include the Waterfall method, Agile method, Cyclic design approach, Double-Diamond method, Pahl and Beitz design method and Stage-gate method. Columns 3 and 4 show the number of participants who follow formal or informal design methods, respectively. Finally, the last column shows the number of participants who agreed with the iterative nature of their design process.

Table 1. Division of participants based on their design methods.

Department	**Participants who follow standard[1] design methods**	**Participants who follow formal[2] design method**	**Participants who follow informal design method but follow design stages[3]**	**Participants who do not follow any design stages**	**Is the process iterative?**	
					Yes	***No***
Mechanical (M)	4	4	0	2	8	0
Chemical (CH)	2	3	3	0	7	1
Civil (C)	0	4	1	1	5	0
Electrical (E)	1	3	2	0	6	0
Total participants	**7**	**14**	**6**	**3**	**26**	**1**
Sub-total	**30**				**27**	
Note: Sub-total participants in the table excludes the associate chairs/deans. The last column excludes associate chairs/dean plus the participants who do not follow any design stages.						

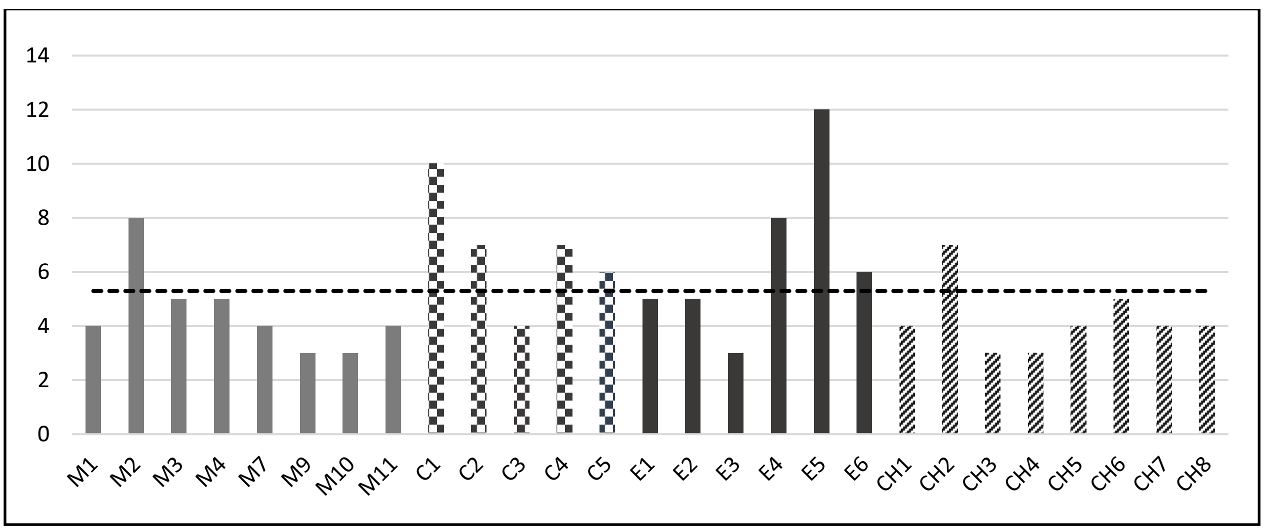

Figure 1. Number of design stages described by each participant.

[1] A renowned formal design method whose step by step design stage is recognized and accepted.
[2] Where participants follow a step-by-step design process, but they do not strictly fall under any of the standard methods.
[3] Participants who did not follow any formal/standard design methods. They were prompted to think and name the design stages, which they follow to design a product.

Each participant described their systematic design process in a different number of design stages. The number of stages described was independent of the discipline. Figure 1 shows the number of design stages as described by the participants themselves. The average number of design stages was 5 and the maximum was 12.

We also compared the participants' description of the design process with the proposed design process. First, the names of the participants' design stages were compared with the proposed stages [16]. For example, a comparison was made between the proposed first stage i.e., *planning* [16] and the participants' first stage of the design process. It was observed that participants named their first design stage as *constraints identification, problem definition, identification of a need,* or other identical stages. Similarly, instead of the *implementation and testing* stage, participants described this stage as *evaluation, refinement, prototyping, testing and data analysis*; while *production* was named as *operation, execution, implementation, project closure,* or other similar stages.

Next, we studied the *activities* occurring during each of the six stages of the proposed design process and compared them with the participants' description of the design process. It was observed that the participants' design stages were identical to several activities occurring inside a proposed design stage. e.g., *concept development* stage in literature consists of activities such as exploring alternatives and ideas, identifying needs, generating specifications, decision matrices, etc. On the other hand, participants described each of this activity as a stage, thus significantly increasing their numbers of design stages. A similar case was seen for *detail design* and *implementation and testing* stage.

Post-Game Design Stages

The design stages renamed by the participants during the cognitive game task, described earlier, were referred to as post-game design stages. The game was conducted with all 34 participants to note their agreement or disagreement with the proposed design stages. If the participant did not rename the design stage, it was considered as his agreement and if the participant renamed the design stage it was considered as his disagreement with the proposed design stage. 11 out of 34 participants agreed to all the six design stages of the process. Out of these 11, 4 were from mechanical; 2 from electrical and 5 from the chemical engineering. 2 out of these 11 participants were those who could not come up with any pre-game stages. Figure 2 shows the percentage of all participants who agreed to the proposed design stages. Figure 3 shows a similar percentage for individual departments.

As can be seen, *planning* as well as *implementation and testing stages* for individual participants were as low as 35% and 50% respectively. Many of the participants claimed that instead of *planning* and *implementation and testing* stages in their curriculum, they have other similar stages such as problem definition, objective, problem analysis, etc. Similarly, there was no *production* stage for many participants from the Civil Department. They argued that instead of a physical prototype their final product was an evaluation report; so, they renamed the last stage of the process as a *final report*. An agreement percentage of 17% from civil shows that a higher percentage of participants renamed the *planning* stage.

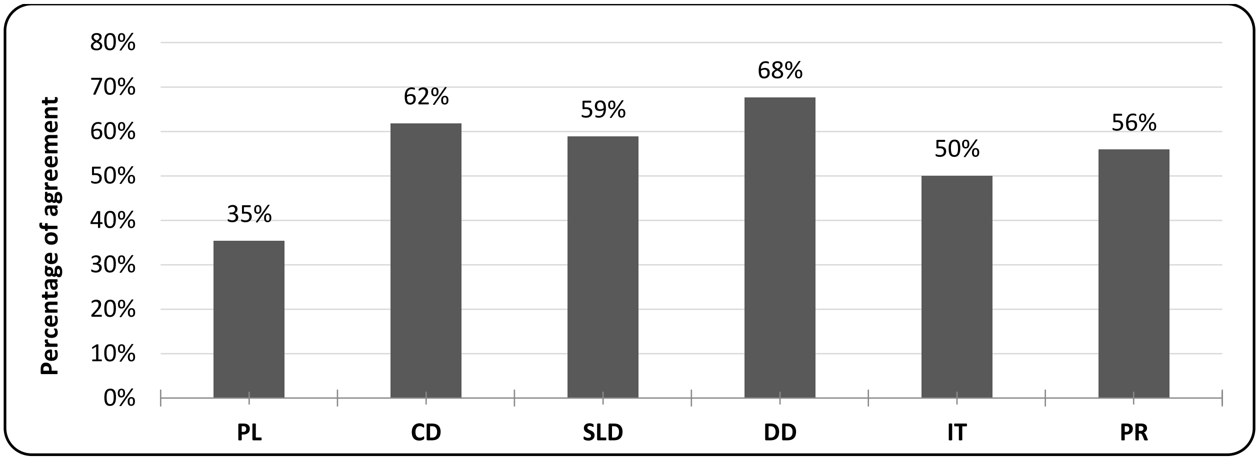

Figure 2. Percentage of participants who agreed to the proposed design stages.

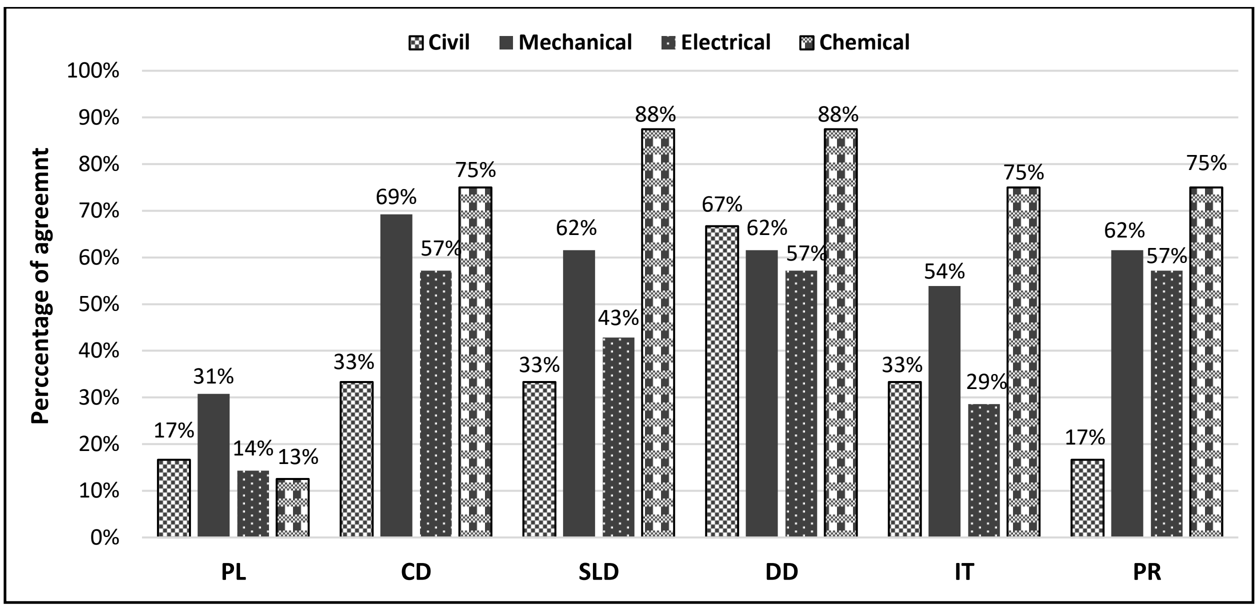

Figure 3. Percentage agreement of participants from each department.

On the other hand, more than 55% of individual participants agreed to other stages of the process, which are *concept development*, *system-level design*, and *detail design* stage because their design courses contained a large content of design from these stages. The agreement is maximum from chemical followed by mechanical discipline, which means the proposed stages were the same as taught by these disciplines.

On average, many participants from civil and electrical disciplines chose to rename most of the design stages thus shown by lower percentages by individual departments. However, renaming the design stages does not mean they did not agree to those stages, rather they found those stages quite relatable to map their own design stages on them. A discussion on the comparison of pre- and post-game design stages is given in the next section.

Comparison of Pre- and Post-Game Design Stages

A comparison of pre- and post-game design stages identified significant results. All participants, except one, agreed that the design process is iterative. The iteration occurs within as well as across the design stages. 90% of participants had no difficulty in describing their pre-game design stages. They had a clear understanding of the design methodologies as well as the formal design stages. 85% of participants started their design process with problem definition/identification of a need or synonymously similar design stage. These design stages may be considered equivalent to the *planning* stage of the proposed process because they are described as its activities in that process. Approximately 29% of participants finished their pre-game design process with *production, prototyping or execution* stages. Participants, who finished their design stages at a stage other than *production*, claimed that they did not teach the course in which the production or prototype was required. They did, however, agree that generally the *production/execution* is the final stage of the design process.

None of the participants reordered the proposed six-stage common engineering design process. Participants showed a consensus on the systematic design stages proposed to them which is represented by the semantically similar names given to those stages. While mapping discipline-specific design stages on the proposed design stages, the majority of the participants covered the *identification of a need/planning, preliminary/conceptual design, detail design, implementation and testing stages*.

It was also observed that, despite the considerable differences between the names given by participants in their pre-game design stages and the names used in the post-game design stages, the majority of them had no difficulty in mapping or renaming the proposed stages to better suit their meaning. The analysis identified that the processes were similar despite the different name and number of design stages.

Conclusion

This paper presented the results of an empirical study on transdisciplinary engineering design processes between multiple disciplines. Results were based on the analysis of the two parts of the interviews: 1) the open-ended questions regarding the design process and its stages as taught by engineering professors for teaching design in their respective disciplines; and 2) the cognitive game task, where participants re-named the stages of the suggested common six-stage engineering design process based on their disciplines.

A comparative analysis between the pre-game design stages of design experts and the proposed common industrial engineering design process shows that the design experts understand the core concepts behind the proposed stages of the engineering design process. The difference between pre-game and proposed design stages was due to the variation in the number of design stages as well as the design content taught in each discipline. Despite this difference, participants understand the design process at an abstract level. When participants were given the proposed six-stage design process, the majority of them had no difficulty in mapping or renaming the design stages. In addition, the mapping did not change the core concepts behind each stage.

Given the comparison and analysis of the mapping of design stages, the study shows that, at a conceptual level, the common design process is independent of the disciplinary boundaries. It means that conceptual similarities do exist between the design stages across multiple disciplines, irrespective of the discipline-specific names given to those stages. Disciplines tend to converge towards similar concepts of the design process before and after playing the game.

The analysis of transdisciplinary process shows that results discussed in the paper are in line with similar industrial findings and therefore, can be considered as a step towards bridging the gap between the engineering design education and industrial practices. The findings of this study should be considered as a basis for developing the undergraduate engineering design curriculum and teaching a common transdisciplinary engineering design process.

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