Transdisciplinary Engineering Design Process:
Building a Common Design Network across Engineering Disciplines

by

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Abstract

Design and engineering design process are necessary components of engineering education. They teach early stage engineering undergraduates about the temporal and organizational nature of the design process and give them the first exposure to the nature of engineering design and its different stages. Currently, in many places, including the University of Alberta, engineering design is taught with a focus on teaching discipline specific design stages and their components. However, Current transdisciplinary product development in industries greatly emphasizes the need for enriching the engineering education curriculum to cope up with existing industrial demands such as giving a clear understanding of a generic product design process while transcending the terminology barriers of discipline specific terminology. Prior industrial research on transdisciplinary product development identifies the existence of a common engineering design process across multiple disciplines. These stages are planning; concept development; system-level design; detail design; implementation and testing; and final production. Noticeable efforts have been done to show the evidence of design process commonalities in the industrial sector, however; very little data is available for similar findings in the field of engineering education.

In the context of the above implication, this thesis is based on an empirical study with an aim to identify commonalities between engineering design processes taught across engineering departments at the University of Alberta's Faculty of Engineering. The data for research is collected through structured one-on-one interviews, conducted with 34 engineering design professors from 8 engineering disciplines namely mechanical, chemical, civil, petroleum, mining and materials, electrical and computer engineering. This study is based on two sections of the interview: open ended questions section on engineering design process and a cognitive game task, based on the aforementioned common engineering design process and Bloom’s Taxonomy.

The purpose of study is to analyse design stages and design activities from multiple disciplines, identify the design concepts, and finally validate the semantic similarity between them. This is achieved through anaytical and computational techniques which are applied using Suggested Upper Merged Ontology (SUMO) and Natural Language Processing (NLP), respectively.

The data collected through this empirical study generated 1566 design activities and 1611 engineering design concepts distributed among six cognitive levels of Bloom’s Taxonomy and across the six design stages for the 4 engineering departments. Initially, SUMO is used to relate design concepts based on their semantic meaning. Next, these semantic relations are verified, through NLP techniques to validate the underlying commonalities between them. In addition, the similarity between disciplinarily design stages is achieved by mapping them on the proposed six-stage engineering design process.

Thus, the results achieved reveal that the commonalities exist across disciplines irrespective of the different terminologies and nature of products. On the basis of above commonalities, this study suggests that the proposed design process can be taught as a common transdisciplinary engineering design process to the undergraduate students.

The methodology applied during this thesis results in finding: 1) a collection of most commonly occurring engineering design concepts in each discipline; 2) achieving a structured mapping of discipline-specific engineering design processes on a common design process; 3) the development of a Transdisciplinary Engineering Design Education

Ontology (TEDEO); and 4) an initial research on the commonality of design concepts between course contents taught in each discipline. These findings, together with TEDEO can be implemented in improving any engineering design curriculum thereby, bringing engineering education in line with the current transdisciplinary industrial practices.

Preface

This thesis is the original work by Mehwish Butt. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project name "Transdisciplinary Design Education for Engineering Undergraduates", ID/No. Pro00068436, January 4, 2017. One journal paper and two conference papers related to this thesis have been submitted or published and are listed as below. The thesis is organized in paper format by following the paper-based thesis guideline. The numbered list represents the respective chapters of this thesis.

2. **Butt, M.,** Sharunova, A., Storga, M., Khan, Y.I. and Qureshi, A.J., 2018. Transdisciplinary Engineering Design Education: Ontology for a Generic Product Design Process. Procedia CIRP, 70, pp.338-343.
3. **Butt, M.,** Sharunova, P.L., Jeunon and Qureshi, A.J., "Transdisciplinary Engineering Design using Ontology and Semantic Similarity based on Data Analysis" International Journal of Technology and Design Education (Under review).
4. **Butt, M.,** Sharunova, A. and Qureshi, A.J., "Transdisciplinary Engineering Design Process: Tracing Design Similarities through Comparison of Design Stages across Engineering Disciplines" American Society of Engineering Education (Under review).

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List of Abbreviations

TEDEO	Transdisciplinary Engineering Design Education Ontology
NLP	Natural Language Processing
CEAB	Canadian Engineering Accreditation Board
NLTK	Natural Language Toolkit library
SigmaKEE	Sigma Knowledge Engineering Environment
SUMO	Suggested Upper Merged Ontology
POS	Part-of-Speech
JVM	Java Virtual Machine

Chapter 1. Introduction

Transdisciplinary product development in today's industry contemplated researchers to identify the need to transform the engineering education from disciplinary to transdisciplinary. They suggested methods to complement the current education approach with a transdisciplinary design approach. One of these methods, also applied in this study, consists of extracting the design concepts common to each engineering discipline. This chapter will introduce the reader to the motivation behind this thesis and the differences between various disciplinary and multidisciplinary approaches. It describes the transdisciplinary education approach and introduces the research. It also defines the preliminary research questions based on the given hypotheses and sets the objectives of the research project.

1.1. Background and Motivation

The growing complexity of artifacts has transformed the literal meaning of design from just being an *outcome* into a complete *process* of creativity (Carpenter, 2016) and problem-solving. Design is an integral component of engineering. Engineering design helps engineers to investigate a scientific problem and create a solution while making the best use of technical skills and rational decision-making (Atila Ertas, 2018). An engineering design process is a fundamental element of engineering design. A simple description of an engineering design process is given by (El-Haik & Yang, 1999) as a constrained process of transforming customer's requirements into complete solutions. Fielden (Fielden, 1963) defines engineering design in the following way: "Engineering design is the use of scientific principles, technical information, and imagination in the definition of a mechanical structure, machine or system to perform pre-specified functions with the maximum economy and efficiency.” Due to technology integration, product design inherently involves interactions between people from multiple disciplines and organizations thus giving rise to a concept of inter-disciplinary and multi-disciplinary design approaches (A. Ertas, Maxwell, Rainey, & Tanik, 2003).

However, from the last two decades, increased globalization of the world has given rise to design problems that are more complex to be tackled by disciplines within their limited traditional boundaries. Technology convergence and specialization of knowledge have rendered the existing disciplinary approaches less effective thereby giving rise to a “Transdisciplinary approach” which, ensures greater collaboration and coherence among disciplines (Kilian Gericke & Blessing, 2013). Transdisciplinarity, a word first appeared in 1970 during a workshop on interdisciplinarity, relates to a methodology of knowledge sharing and application *between, across and beyond* all disciplines (Nicolescu, 2005). Peterson (Peterson & Martin, 2013) defined transdisciplinarity regarding collaboration among specialists and scholars from multiple disciplines or fields to integrate concepts to form a product. Various authors (A. Ertas et al., 2003; Gumus, Ertas, Tate, & Cicek, 2008; S.Upham, 2001) have described the detailed concept of transdisciplinary approach in industry and education (Kilian Gericke & Blessing, 2013; A. Qureshi et al., 2013; A. J. Qureshi et al., 2014), the term is still interchangeably used with inter and multidisciplinary approaches.

1.2. Intra-, inter-, multi- and transdisciplinary design approaches

To conduct this research and to help the readers distinguish between different types of approaches, it is important to define and distinguish between the meaning of terms disciplinary, inter-disciplinary, multi-disciplinary and transdisciplinary.

Discipline is defined as an area of study that has tools, terminologies, and methods unique to it (Atila Ertas, 2010). The disciplinary design is carried out in a single discipline, within the framework of technically, and methodologically homogeneous field. In this design environment, disciplines are far apart from each other with no information and knowledge sharing across them. As a result, they can no longer accommodate individually, the complex technology-driven nature of the modernized world. This gap between disciplines is somewhat covered by multi-disciplinary and inter-disciplinary approaches.

A multi-disciplinary design approach deals with the interaction of multiple disciplines working for a common design goal. The experts from each discipline give input and receive outputs from other disciplines to develop a product which, otherwise could not be developed by single disciplines (Blevis & Stolterman, 2008). However, the limitation of multi-disciplinary lies in the notion that each discipline works primarily with its own tools, methods, and framework. Klein (Klein, 1996) describes the multi-disciplinary activities as additive rather than interactive, i.e., the major part of activities are carried out in a disciplinary fashion, and the findings are accumulated in the end.

An interdisciplinary design is more robust and a step above the multi-disciplinary design approach. It tries to occupy the distances between disciplines by providing a coherence between knowledge and concepts of the disciplines involved (Petts, Owens, & Bulkeley, 2008). It integrates separate bodies of specialized data, methods, tools and concepts to create a mutual understanding of a problem between disciplines (Huutoniemi, Klein, Bruun, & Hukkinen, 2010). Interdisciplinary, similar to multidisciplinary, overflows the traditional boundaries of disciplinary approach. Apart from the advantages that inter-disciplinary provides over multi-disciplinary design approach, disciplines still keep their own boundaries. Inadequate interdisciplinary interaction, lack of common terminologies and limited knowledge sharing hinder the necessary involvement of disciplines, thus giving rise to a transdisciplinary approach.

A transdisciplinary design is defined as “An integrative process in which researchers work jointly to develop and use a shared conceptual framework that synthesizes and extends discipline-specific theories, concepts, methods, or all three to create new models and language to address a common research problem” (Rosenfield, 1992). Transdisciplinarity is complementary to disciplinary approaches (Nicolescu, 2005) and indicates the unification of knowledge that exists between, across and beyond all disciplines (Nicolescu, 1999a). Transdisciplinarity transcends the disciplinary boundaries and goes for full disciplinary integration, which is a step ahead of interaction. Some might argue that interdisciplinary is similar to transdisciplinary but (Gibbons, 1994) differentiates interdisciplinary and transdisciplinary as “interdisciplinary approaches are characterized by an explicit formulation of a uniform, discipline-transcending terminology or a common methodology. A transdisciplinary approach goes one step further, as it is based upon a common theoretical understanding, and must be accompanied by a mutual interpenetration of disciplinary epistemologies.” The idea of a three-dimensional transdisciplinary vector (Koizumi, 2001) provides quite enough support to the level of integration of multiple disciplines in comparison of two-dimensional multi- or interdisciplinary co-operation. The resulting force in a transdisciplinary vector represents the emergence of an integrated framework that might result in the form of a new discipline. The emergence of this new unified discipline depends highly on the level of integration between the disciplines.

1.3. Transdisciplinary engineering design education

An engineering design process is a distinguishing activity during product design. Engineering design is a core element of engineering practice (Dinsdale, 2014) and an integral component of engineering education. The complex transdisciplinary nature of problems requires promoting a common understanding of design and engineering design process among students so that they can build effective solutions to these problems. The current disciplinary approaches identified a lack of integration and involvement of disciplines, which is necessary for cultivating this common understanding. According to (A Ertas, Tanik, & Maxwell, 2000), the disciplines in engineering education are surrounded by boundaries in the form of discipline specific tools and terminologies. Due to these limitations, although engineers can communicate effectively within their disciplines, however, it is difficult for them to communicate outside their disciplines. Given this context, (Nicolescu, 1999b) considers transdisciplinary education approach indispensable. The example of Embedded Cruise Control system design given by Tanik and Chan (Tanik & Chan, 1991) also necessitates the concept of transdisciplinary integration to solve complex problems. Transdisciplinary education combines the meta-level knowledge and concepts and develops a transdisciplinary mindset in students (Madni, 2007). To enhance the current disciplinary education system to transdisciplinary, (Butt, Sharunova, Storga, Khan, & Qureshi, 2018; A. Ertas et al., 2003) proposes a methodology to extract common elements of design from each discipline and then build upon these concepts, a new transdisciplinary system of education. The only way to extract the common concepts is by doing a detailed analysis and research of the current education system with a focus on *"identification of design commonalities among disciplines."*

1.4. An introduction to Bloom's Taxonomy

Bloom's Taxonomy is a framework for classifying the educational goals and objectives in order to improve students' learning. It was developed by Benjamin Bloom in 1948 and later revised by one of his students, Lorin Anderson (Anderson et al., 2001). The taxonomy is divided among three domains of learning namely cognitive, affective and psychomotor domain (Cox & Wildemann, 1970; D.R. Krathwohl, Bloom, & Masia, 1964; Simpson, 1966). The work related to this thesis is linked with the Bloom's cognitive domain only. According to Bloom's taxonomy of cognitive domain, thinking is classified into six hierarchical levels of complexity. The first three levels are basic or lower levels and the next three are complex or higher level of thinking. Each higher level in the taxonomy is more complex than the preceding level whose understanding and knowledge is necessary to move to the next higher level. These six levels are knowledge, comprehension, application, analysis, synthesis and evaluation domain. The detail description can be found in (Anderson, 1994; Bloom's, 1965), however, in order to build reader's understanding, each level is defined below. The definitions are described based upon the understanding from (Bloom's, 1965; Forehand, 2011; David R. Krathwohl, 2010).

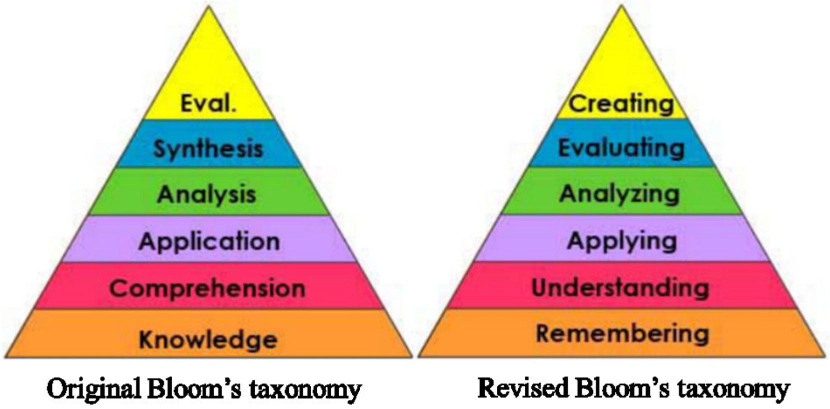

Figure 1 Bloom's Taxonomy: original vs revised (Anderson, 1994)

Knowledge: This level refers to remembering the previously learnt information i.e., observing if an object knows basic information about a subject.

Comprehension: This level refers to understanding the meaning behind the basic concepts and the capacity to interpret them during a problem.

Application: This level refers to the ability to implement the concepts wherever required. It also includes modifying and applying the available information according to the problem situation.

Analysis: This level refers to the activity of breaking down a bigger component or problem into smaller parts, which is helpful to conclude or evaluate a problem.

Synthesis: This level refers to collecting and synthesizing the results after analysis.

Evaluation: This level refers to drawing conclusions and presenting the results based on the conditions initially presented.

This study uses Bloom's Taxonomy for various reasons (Sharunova et al., 2017; Sharunova, Butt, & Qureshi, 2018): First, it uses the action verbs from the Taxonomy to generate design activities which generally occur during an engineering design process. The action verbs used for this study are given in (Sharunova et al., 2018). Second, the taxonomy is used to assess the cognitive aspects involved during the design process by tracing the pattern of design experts' thinking. It also provides a common language to compare the cognitive patterns of design between different individuals as well as finding the overlap or commonalities between their design thinking. Third, it is a source of measuring students thinking ability and therefore a powerful tool to design course curriculum.

1.5. An introduction to research

The research objectives are developed to successfully implement an empirical research project at the University of Alberta entitled “Transdisciplinary design education for the first-year engineering undergraduates.” The project was initiated with a goal to introduce a first-year design course that will teach the basic engineering design process to the students. The objective was to develop a common understanding of a design process among students, irrespective of disciplinary context, terminology, and nature of the product. The objective will be achieved by identifying the commonalities of the engineering design process and its stages across the 4 engineering departments in the Engineering faculty, i.e., Mechanical Engineering, Chemical and Materials Engineering, department of Civil and Environmental Engineering, Electrical and Computer Engineering. Following paragraph briefly describes the current education system for the first-year engineering undergraduates.

At present, the number of students inducted to first-year engineering, study a common first-year curriculum which consists of basic courses, e.g., physics, computer, mathematics, algebra, etc. They also have few courses that cover some general introduction to the engineering profession, e.g., engineering disciplines and work opportunities, etc. Once students finish their first year, they have an option to choose their area of specialization, based on their interests as well as their grades, from one of the 4 engineering departments. The students complete rest of the 3 years of study in their specialized disciplines with a strong focus on discipline specific courses.

The problem initiates when students branch out into different disciplines, without studying any course on the fundamentals of design; they learn only discipline specific design thinking, processes and methodologies. As a result of limited interaction with other disciplines, the design knowledge they learn is also limited to discipline specific tools, e.g., terminology, context, and nature of the product. They find it difficult to develop a common understanding of a design process. When these students step out into transdisciplinary environment in industry, despite a strong grip on their discipline, they have weak connections with other disciplines.

This thesis focused on transdisciplinary engineering design processes, encompasses the results of an empirical study, which was designed to collect data on engineering design processes from 8 disciplines: Electrical Engineering, Mechanical Engineering, Chemical Engineering, Civil Engineering, Computer Engineering, Petroleum Engineering, Material Engineering and Mining Engineering. The study consisted of 34 structured one-on-one interviews with professors from the engineering faculty who teach engineering design courses to 2nd, 3rd and 4th year students. Each interview was one-hour long and divided into 3 sections: the open-ended questions, a written questionnaire, and a cognitive game task. The interviews are described in detail in (Sharunova et al., 2018) and the coming chapters.

1.6. Research objectives

In the context of the above description, this research has the following objective:

> "*To identify the similarities between design concepts of multiple engineering disciplines and to propose a common engineering design process; whose design stages are widely accepted and applicable across engineering faculty irrespective of the terminologies and the nature of the product taught across these disciplines*."

The research is built on the following hypotheses:

1. The major engineering disciplines teach a common engineering design process to students irrespective of the terminology and the nature of the product.
2. The stages of engineering design processes are conceptually similar across the engineering disciplines, regardless of the terminologies used to name them.

The objective of the research is divided into the following action items:

01. Develop a Transdisciplinary Engineering Design Education Ontology (TEDEO) to represent a semantic relation between design concepts from each discipline.
02. Verify the semantic relations between design concepts through computational Natural Language Processing (NLP) techniques and investigate the nature of design concepts taught to the students.
03. Investigate the abstract level similarity of design stages across the disciplines involved, through extensive literature review and mapping. Identify the existence of a common engineering design process agreed upon by all disciplines.

To fulfill the above objectives, we used NLP techniques and cognitive approach to transform the raw data obtained from interviews into a structured set of information. It generates the following information:

1) A collection of engineering design activities, i.e., combinations of verbs and nouns proposed by participants during a cognitive game task.

2) A division of design concepts into different cognitive levels based on the extrinsic information they carry during an engineering design process.

3) A comparison of disciplinary design stages mapped on a common engineering design process.

The research has fulfilled the objectives through following novel contributions, which are explained in the coming chapters:

1) Developing an engineering-cognitive game task by combining a common six-stage engineering design process with action verbs from Bloom's Taxonomy.

2) Development of a Transdisciplinary Engineering Design Education Ontology (TEDEO).

3) A semantic similarity measurement method, which uses NLP techniques in combination with hypernyms, to verify semantic links between engineering design concepts.

4) "Bloom's distribution method for design concepts" designed to trace the distribution of design concepts/nouns among six cognitive domains of Bloom's Taxonomy. The pattern thus formed, describes the importance and usage of each cognitive domain during the design process.

1.7. Organization of the thesis

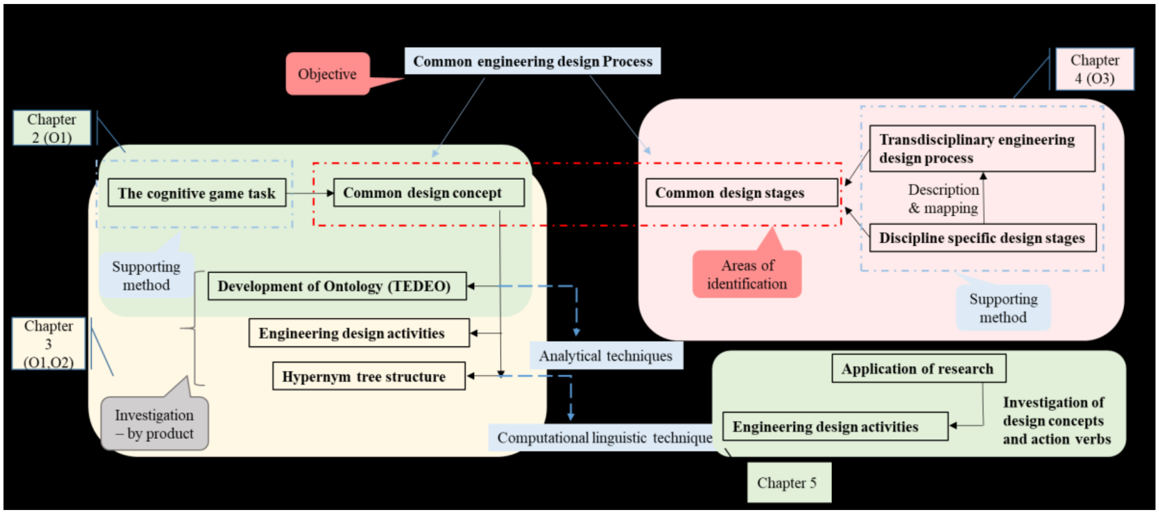

Figure 2 Organization of the thesis

The thesis consists of 6 chapters. Chapter 0 briefly introduces transdisciplinary engineering design, its significance in education and the research objectives. Chapter 0 discusses TEDEO framework and its objectives. It identifies and builds a semantic network between design concepts for the first stage of an engineering design process. This chapter partly fulfills the action item 1. Chapter 3 presents the complete TEDEO for all the stages of the design process. It also implements NLP techniques to validate the semantic network thus created across disciplines. It analyzes the distribution of design concepts and design activities along the cognitive domains of Bloom's Taxonomy. It validates our first hypothesis as well as finishes the action item 1 and 2. Chapter 4 presents a comparison of discipline specific engineering design stages and their mapping on a reference six-stage engineering design process as described by participants of the empirical study. It validates our second hypothesis and finishes the last action item. Chapter 5 is an application of research that sets our future objectives while chapter 6 concludes the thesis. Figure 2 Organization of the thesis shows a depiction and the relationship between each chapter.

Chapter 2. Transdisciplinary engineering design education: Ontology for a generic product design process

This chapter is based on the results obtained from the interview series that was part of the empirical study and contributes towards validating the first hypothesis of the research. The chapter is a modified version of original paper “Transdisciplinary engineering Design Education: Ontology for a generic product design process”. It aims to validate the hypothesis that engineering disciplines in education share a common engineering design process. It describes the methodology for the development of a Transdisciplinary Engineering Design Education Ontology (TEDEO) for eight major engineering disciplines namely mechanical, chemical, civil, petroleum, materials, mining, electrical and computer engineering. It proposes a high-level transdisciplinary engineering design process that consolidates a diverse array of engineering terms and concepts into a generalized model.

2.1. Introduction

Design is one of the fundamental concepts in engineering education. Design and engineering design process serve as a common thread that ties engineering disciplines together (Tanik, M. M., Yeh, R. T., & Ertas, 1995). Design process education transfers basic design knowledge to students and builds their understanding of how industries design and develop their products. Due to increasing demand of technology innovation across industries, the existing practice of product development process has transformed from mono-disciplinary to transdisciplinary (K. Gericke & Blessing, 2012; Kilian Gericke, Adolphy, Qureshi, Blessing, & Stark, n.d.; Kilian Gericke & Blessing, 2013; A. Qureshi et al., 2013; A. J. Qureshi et al., 2014). In order to keep up with current industrial practices, it is necessary to promulgate the knowledge of a transdisciplinary design process in engineering students. There are several barriers to a transdisciplinary design process including discipline specific concepts, tools and terminologies. These barriers result in an inadequate communication and a lack of technology integration among these disciplines, which prevents the use of shared knowledge and methodologies to achieve the best possible design. Table 1 summarizes the common engineering design stages followed by multiple disciplines in educational as well as industrial design process environment. It has been observed that a lack of transdisciplinary concept formation at the early stage of different undergraduate studies (e.g., Mechanical Engineering, Civil Engineering, Electrical Engineering etc.) poses great difficulty to fresh graduates at the time they enter industries. They must stretch their circle of knowledge beyond their learning experience to gain insight into an area other than their specialized discipline (Sharunova et al., 2017; Zaharim, Md Yusoff, Mohamed, & Muhammad, 2009).

One way to develop the concept of transdisciplinarity in education is through the presentation of unified product development and design process. We suggest that this can be done by tracing engineering design processes in each discipline, analyzing their knowledge base in depth and highlighting the common design stages based on the design activities conducted during distinct phases of a design process (A. Ertas et al., 2003).

This paper is based on a research project that intends to explore the commonalities of engineering design process at the Faculty of Engineering at the University of Alberta. The goal of the research is to identify similarities across multiple engineering disciplines and come up with a common engineering design process, which is applicable across these disciplines. This paper presents the results of an empirical study conducted as a part of the large research project.

Author	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Philippe Krutchen	Inception (Lifecycle objective)	Elaboration (Lifecycle architecture)	Construction (Initial operational capability)	Transition (Product release)	-	-
Ulrich and Eppinger	Planning	Concept development	System-level design	Detail design	Testing and refinement	Production Ramp-up
Howard et all	Preparation	Design	Pre-construction	Construction	Use	
VDI 2221	Clarification of task	Specification	Conceptual design	Preliminary layout	Definitive layout	Solution & Documentation
Artila Ertas	Recognition of needs and requirements	Conceptual design	Feasibility study and concept reconsideration	Preliminary design	Final design	Production and testing

Table 1 Common engineering design stages (Cross, 2008; Atila Ertas, 2010; Howard, Culley, & Dekoninck, 2008; Kruchten, 2004; K. T. Ulrich & Eppinger, 2011)

The study consists of a series of individual interviews with engineering professors who teach design courses in the Faculty of Engineering. The scope of this paper is limited to the engineering-cognitive exercise which was carried out during the interview. The motivation behind this exercise was to assess the design thinking of engineering professors and build the TEDEO.

This research uses design concepts from each discipline to build an integrated network of the knowledge base of design across all of the engineering disciplines. This network traces the aspect of the design process that are common to all engineering disciplines. The integration of engineering knowledge and design thinking from multiple perspectives will foster systems thinking approach in the fresh graduates. Systems thinking involves an understanding of interconnections between various components of a system and how each component functions as part of a system. They will be able to understand at an abstract level, a multifunctional definition of engineering systems thinking (Frank, 2000; Frank & Waks, 2001). One of the widely accepted methodologies for comprehensive knowledge tracing is an ontology. Ontologies are widely used for different purposes like natural language processing and knowledge management tools. They classify and categorize design concepts according to their intrinsic and extrinsic properties. Domain-independent ontologies are developed by mapping characteristics that are common across the domains under investigation (2017). At a minimum, an engineering ontology is a collection of engineering vocabularies, concepts and constraints as well as a language tool to link these vocabularies together through the concepts and their relations (Štorga, Andreasen, & Marjanović, 2010).

2.2. Research hypothesis and approach

The study is based on empirical research carried out with eight major engineering disciplines in the Faculty of Engineering, University of Alberta. These eight engineering disciplines are Chemical Engineering, Mechanical Engineering, Civil Engineering, Electrical Engineering, Computer Engineering, Petroleum Engineering, Materials Engineering and Mining Engineering.

This research aims to validate the hypothesis that "*the major engineering disciplines teach a common engineering design process to students irrespective of the terminology and the nature of the product*". At the end of research project, we will be able to answer the following questions:

1. Does any similarity exist in the design processes of the studied disciplines? Do these processes follow similar design stages? Do these similarities persist irrespective of the content of each stage?

2. How can the terminology gap in the current disciplinary frameworks be reduced to incorporate concepts of transdisciplinary engineering design process?

The proposed solution for finding commonalities across the disciplines is a Transdisciplinary Engineering Design Education Ontology (TEDEO). This paper presents first part of the methodology by which TEDEO was developed which includes management and development of ontology. The section below describes the methodology that was adopted during development of TEDEO.

2.3. Development cycle of TEDEO ontology

The methodology for developing the TEDEO was a bottom-up approach, which enabled the construction of generic ontologies using domain-specific knowledge. Developing TEDEO was a seven stage process, shown in Figure 3. These stages were: *planning, data collection, terminology identification, categorization, formalization and implementation, refinement* and *documentation*. The activities performed during each stage are described below.

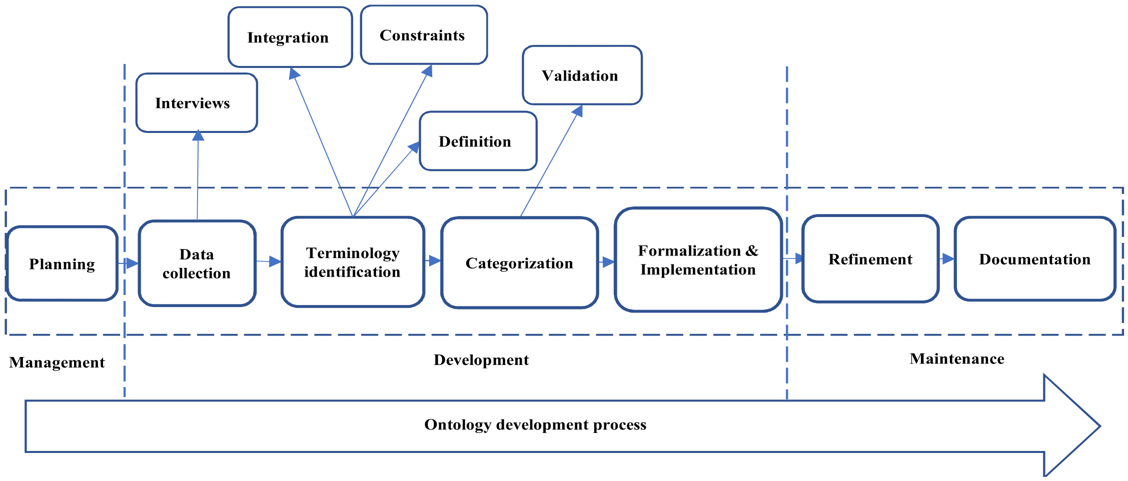

Figure 3 TEDEO development process

2.3.1. Planning

This stage included initial planning for the ontology building scheme. The activities in this stage included interviews with engineering professors at the Faculty of Engineering, collection of their lecture materials, building the Taxonomy, identification of a language tool for building the ontology, and listing the external and internal sources of knowledge as well as other management activities.

2.3.2. Data collection

The data collection stage consisted of 34 individual interviews carried out with engineering professors from multiple disciplines who teach design courses in the Faculty of Engineering. Interviews were one hour long and included a written questionnaire, open-ended questions related to engineering design and an engineering cognitive game task based on Bloom's Taxonomy. During the interview, all participants were asked about the components of engineering system, engineering design process, stages of engineering design process and design process methodologies.

The cognitive game task was developed to obtain a collection of terms most commonly used by engineering design experts from different disciplines and to observe how different engineering activities are distributed along the design process. The game consisted of three parts:

Providing participants, a six-stage engineering design process proposed by Ulrich and Eppinger (K. T. Ulrich & Eppinger, 2011). The process was chosen based on current research on transdisciplinary engineering design process (K. Gericke & Blessing, 2012; Kilian Gericke & Blessing, 2013; A. Qureshi et al., 2013; A. J. Qureshi et al., 2014) as well as the generic design stages and the description of design activities which occur inside these stages. The six stages used were *planning, concept development, system-level design, detailed design, implementation and testing*, and *production*. In order to see how discipline experts interpret the design process; participants were asked to name the commonly used design stages of their own discipline. They were also asked to map their engineering design stages over the given six-stage design process. The results of this activity are out of the scope of this paper and will be released in a separate study.

In the next stage, each participant was given 42 randomly mixed verbs, which come from Bloom's Taxonomy Cognitive Domain: 7 unique verbs from each of the six cognitive levels (David R. Krathwohl, 2010). Participants were asked to come up with one or two engineering-related nouns for each verb. Participants were allowed to use the same engineering-related nouns more than once if they choose to.

Finally, the combination of each verb-noun was treated as a type of activity. All participants placed this activity at the most appropriate design stage as per their discipline and understanding of the design process.

2.3.3. Terminology identification

At the end of this exercise, a total of 1611 nouns were collected that were distributed across six design stages as below: 263 nouns in Stage 1; 369 nouns in Stage 2; 274 nouns in Stage 3; 292 nouns in Stage 4; 299 nouns in Stage 5 and 114 nouns in Stage 6.

The raw data for first design stage was analyzed to prepare a unique list of nouns that are non-repetitive. At the end of raw data analysis, the total nouns left in the first design stage were 101. To ensure the string of nouns remained intact with engineering design domain, the meaning of each noun was restricted by properly defining them. The most suitable definitions were selected that relate the nouns to engineering field. The definitions were selected irrespective of the usage of the nouns with verbs. To choose definitions a knowledge base was required, which had to be as discipline-independent as possible. After a thorough literature review, the Suggested Upper Merged Ontology (SUMO) (http://www.adampease.org/OP/) was selected as a knowledge base for developing upper-level ontology. SUMO can describe the generalized engineering design process concepts that are applicable to all engineering disciplines. SUMO is intended to express and provide definitions for the most basic and universal concepts that are abstract, philosophical, and general enough to address a broad range of different domain areas. SUMO was chosen because it has several advantages over other available ontologies. First, it is an effort from an open source engineering community, so it has a very large class of users. Second, it is a huge database with a combination of engineering and information sciences (Štorga et al., 2010).

A detailed study about the classification of entities in engineering design domain was done by Storga et al.(Štorga et al., 2010; Storga, Andreasen, & Merjanovic, 2005) which we used as the foundation of TEDEO. An overview of the top-level classification is given in Figure 4 (Štorga, Marjanović, & Andreasen, 2007). Figure 4 also shows the project-specific top-level classes and their subsequent subclasses that are described in the next section.

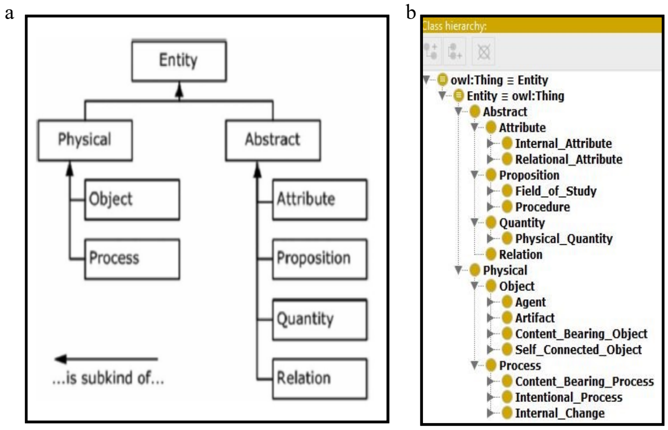

Figure 4(a) SUMO classification; (b) TEDEO top-level classes

2.3.4. Categorization

Once the nouns were defined, the next stage was building the Taxonomy for the ontology. The categorization places nouns into different classes based on their definition and the relation one noun has to another. This stage helps in building the Taxonomy for ontology. It begins with specialized domain-level concepts called instances, which are generalized into one of the six top-level categories of physical and abstract. The categories consist of numerous classes and subclasses. A subclass is a group of entities that share common characteristics, which are different from other subclasses (Štorga et al., 2010). Each entity in a sub class is called an individual. SUMO maps the domain level concepts of the same kind based on their semantic relations and places them together under one subclass. Therefore, individual entities from different disciplines may group together in one subclass. Subclasses are linked with each other through properties based on binary relations between them. These binary relations represent the semantic association between subclasses and the individuals that they contain. A set of semantically related subclasses merge into a higher level generalized concept in the form of a class. The definitions of classes and subclasses, which were substantiated in the TEDEO case project, are taken from SUMO and summarized below with examples.

The *Object* corresponds roughly to the class of ordinary objects. The Object is specialized into *Artifact*, *Agent*, *Self-connected object* and *Content Bearing Object*. An A*rtifact* is an object that is produced. E.g. engine and mill as proposed by participants from Petroleum and Electrical engineering respectively. The *Agent* is a subclass of objects and contains individuals that can act on their own to bring changes in the world. E.g. team and company as proposed by participants from Civil and Mining Engineering respectively. The *Self-Connected Object* is a subclass of objects made up of one part only that cannot be disconnected into two or more parts. E.g., material and electricity as proposed by participants from Mechanical and Civil Engineering respectively.. The *Content Bearing Object* that contains information. E.g., literature and database as proposed by participants from Civil and Mechanical Engineering respectively. The *Process* is a phenomenon that is sustained or marked by gradual changes through a series of states. The Process is specialized in *Content Bearing Process*, *Intentional Process,* and *Internal Change*. The *Content Bearing Process* is a subclass of the process, which involves the content of information. The *Intentional Process* is defined as a process that is performed with the specific purpose behind it. E.g., learning and decisions as proposed by participants from Civil and Mechanical Engineering respectively. The *Internal Change* is a process where the internal property of an entity is changed. E.g., listening as a biological change and constraints as a quantity change as proposed by participants from Electrical and Chemical engineering respectively.

Attribute are the qualities, which we cannot or choose not to reify into subclasses of. E.g., requirement and limitations in Objective Norm as proposed by participants from Computer Engineering and Mechanical Engineering respectively. Leader and User in social role as proposed by participants from Electrical and Computer Engineering respectively. Knowledge and professionalism as Psychological attributes proposed by Electrical and Mining Engineering respectively.

The *Propositions* are entities that express a complete set of thoughts. E.g., meaning, assumptions and ideas as proposed by participants from Mechanical, Mining and Chemical engineering respectively. System and methodologies in Procedures as proposed by Electrical and Chemical Engineering respectively.

The *Quantity* describes how much of something is there. E.g., mine-life and stages in Constant Quantity as proposed by participants from Mining and Mechanical Engineering respectively The *Relations* are generic associations shared between individuals.

2.3.5. Validation

Before building the Taxonomy, the categorization was validated by checking its reliability. The reliability is checked using Cohen's Kappa coefficient, which calculates the inter-rater reliability. Inter-rater reliability is a means to calculate the extent of agreement between two researchers/validators. It measures the actual agreement between the coders and subtracts any agreement that occurred by chance (Harwood & Garry, 2001; Mchugh, n.d.). The Kappa co-efficient is calculated by creating a matrix where the columns and rows represent each of the categories to be rated by rater 1 and 2. In the current research, two matrices were created. One for the classes of the Physical, Abstract, and the other for their six-subclasses. The numeric count of each category is evaluated by using the following formula:

$$K_p = \frac{P_a - P_c}{1 - P_c}$$

Where K_p is the kappa coefficient; P_a is the agreement actually observed between the coders/rater while P_c is the agreement by chance between them.

The range of the value of kappa coefficient is given below.

$K_p = 0$	No agreement
$0 < K_p \leq 0.2$	Slight agreement
$0.2 < K_p \leq 0.4$	Fair agreement
$0.4 < K_p \leq 0.6$	Moderate agreement
$0.6 < K_p \leq 0.8$	Substantial agreement
$0.8 < K_p \leq 1$	near to perfect agreement

The value of kappa coefficient was calculated as described in (Harwood & Garry, 2001). The validation and results of calculation are explained below.

Once the categorization was done, experts from the relevant research area analyzed the definitions and categorized the terms independently. Depending on the value of Kappa coefficient, the reliability was evaluated. First the results were compared between the two top level classes of Physical and Abstract. The value of Kappa coefficient was 0.52 showing moderate agreement. Second the results were compared between the six subclasses of Physical and Abstract. The value of Kappa coefficient was 0.60. It was observed that most of the disagreement was due to the different definitions chosen by each rater. To improve the value of coefficient, those definitions were revisited and the terms of disagreement were re-categorized. The new coefficient calculated was 0.88 for two top-level classes. There were total six out of 101 terms where the raters had a disagreement on the categorization. The value of Kappa coefficient was 0.79 for the six subclasses which was very close to high reliability. The percentage agreement of each of the categories was 98% for Physical, 91% for Abstract, 94% for Process, 93% for Object, 80% for Attribute, 77% for Proposition and 67% for Quantity.

2.3.6. Formalization & Implementation

The next step after validation was the ontology formalization and implementation, which includes Taxonomy building. The tool used for building the Taxonomy was Protégé (https://protege.stanford.edu/). Protégé is an open source tool developed at Stanford University that has a large community of users. The reason for using Protégé in this research project was that it represents domain information in a variety of ways.

It allows users to build classes that represent concepts in a domain, sibling classes that are direct subclasses of the same class, and individuals called instances (Noy & Mcguinness, 2000), which are most specialized concepts of a knowledge database. The complete Taxonomy for the first design stage with 101 entities is shown in Figure 5. Once the Taxonomy was built, the next step was to code the relations through properties, which link classes, their specialized sub-classes, and the individuals within or across these subclasses. Different classes may share the same individuals. Different individuals in different classes can be linked to each other through various object properties. Some examples of Object properties used in TEDEO are thatInvolvesChemicals, isCapableOfPerception, isCategorizedInto. Another important aspect is the visualization of the ontology in protégé, which is the representation mechanism for ontologies and knowledge bases. It facilitates many ways to view the ontology structure. OwlViz and OntoGraf are widely used in current project and the output from OntoGraf, which is a ".dot" file, can be used to visualize complete ontology and its descriptive view in Graphviz. The concepts are built using the individuals, subclasses and their classes defined in section 2.3.4. Figure 6 represents a small section of objects related through properties defined for them.

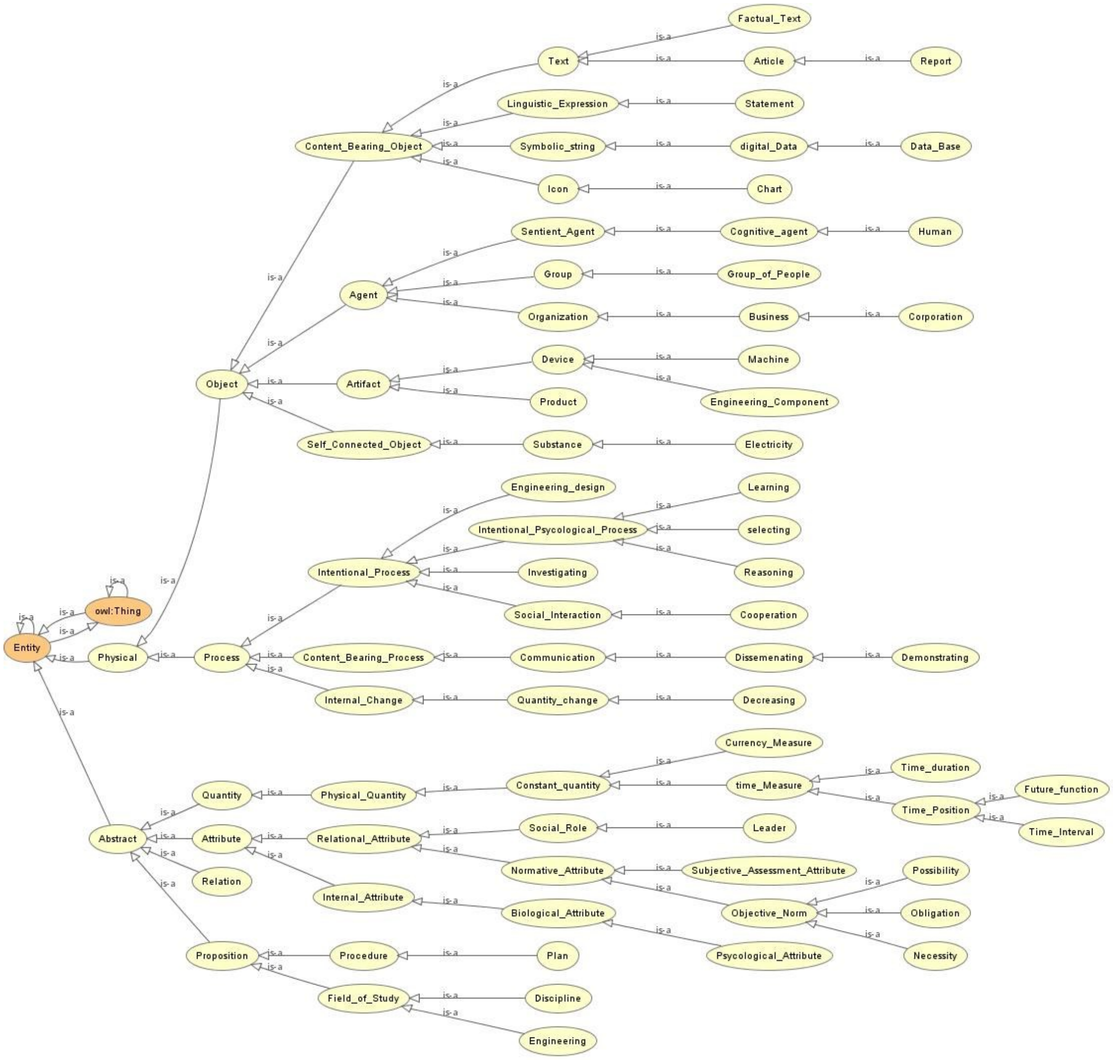

Figure 5 TEDEO class structure

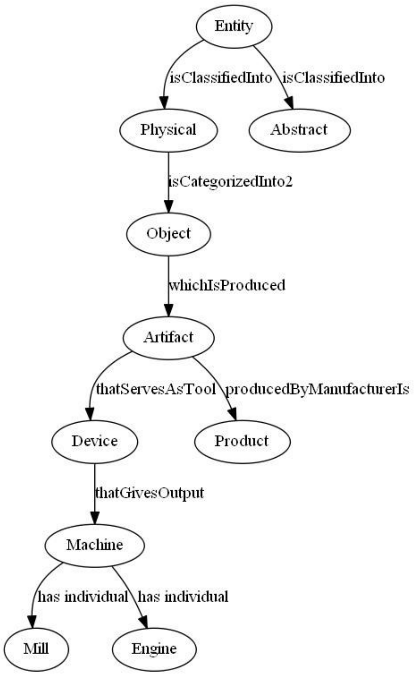

Figure 6 Visualization of Artefact

2.4. Conclusion

In this paper, a methodology for creating a Transdisciplinary Engineering Design Education Ontology using a bottom-up approach and results from empirical study are presented. In particular, the results for the first design stage of a transdisciplinary engineering design process were shown, which support the hypothesis that *engineering disciplines share a common engineering design process despite the differences in terminology and the nature of the product*. The analysis shows the following results in favor of the hypothesis:

1) The existence of the Planning stage in any engineering design process cannot be denied. Design activities performed across all disciplines are represented in a different manner but semantically they refer to the similar concepts of processes, objects, and attributes across multiple disciplines.

2) Similarly, the terminology used across the disciplines is linguistically different but by building conceptual relationship across the disciplinary domain, they can be well aligned semantically.

The next step of this research project is to analyze nouns for all six design stages and build a Taxonomy for a complete engineering design process. Based on the semantic relation between the nouns in each design stage, every department will be linked to the shared concepts in that stage. These shared concepts will highlight the existence of transdisciplinary links across disciplines. The concept of semantic interaction between individual components of each discipline will also help students to understand the dynamic complexity of any given system. Thus engineers with transdisciplinary approach will not only understand the generic components of an engineering design process, they will tend to have an understanding of how components and sub-systems integrate to form a complete system. TEDEO will be further refined by data analytics of the course material provided by professors. The nouns thus obtained, will be embedded in the current Taxonomy to enhance the knowledge it contains and to refine the existing links between the concepts across disciplines. The development of TEDEO will help engineering students to understand the integrated design process and at the same time support them in coping with current challenges of transdisciplinary industrial environment. It is also believed that the generalized methodology for TEDEO is not only limited to engineering but it can also be applied in fields other than engineering.

Chapter 3. Transdisciplinary engineering design: Using ontology and semantic similarity on data analysis

The previous chapter presented development process of TEDEO for the first stage of a six-stage common engineering design process. Built upon the aforementioned process, this chapter presents the TEDEO development process for all the six design stages and analyses the relation between design concepts based on their semantic meaning. This chapter also explains the NLP techniques, which were used to verify these semantic relations. Based on the essence of transdisciplinarity; it analyses the distribution of design concepts across the design stages. It also discusses the implications of using Bloom's Taxonomy in relation to design concepts as well as the design activities.

3.1. Introduction

Engineering design is a problem-solving activity (Chandrasekaran, 1990). It involves technical skills (Abdullah et al., 2007) and creativity (Carpenter, 2016) and makes the best use of available data, information, and knowledge. Design and engineering design process are integral components of an engineering education that binds engineering disciplines together (Tanik, M. M. et al., 1995). Recent study (Sharunova et al., 2017) in engineering education identified some of the fundamental barriers engineering institutes face while teaching design. These include the absence of a common terminology and understanding of design process between students from multiple disciplines, that is, a lack of transdisciplinarity (Atila Ertas, 2018). The barriers between disciplines limits transdisciplinarity in education (Atila Ertas, 2010; Tanik, M. M. et al., 1995). As a result, when engineering graduates enter industry, they exhibit a narrow design approach in terms of skills required by industry, which include technical knowledge as well as generic skills

(Md Yusoff et al., 2009; Nguyen, 1998). Researchers (K. Gericke & Blessing, 2012; Kilian Gericke & Blessing, 2013; A. J. Qureshi et al., 2014) argue that transforming the engineering curriculum so that it is in line with current industrial demands, means that engineering education must go beyond the discipline-based approach.

Building on these findings, this paper is in a series of an empirical study and project on "Transdisciplinary Design Education for Engineering Undergraduates". The research was conducted at the Faculty of Engineering, University of Alberta (Sharunova et al., 2017). The objective of this project is to provide a first year, systematic engineering design process course as a precursor to the discipline-specific engineering design courses offered in 2nd, 3rd, and 4th year. A first-year engineering design course, common across all disciplines, will provide students a unique opportunity to acquire a common, transdisciplinary knowledge. This project aims to achieve this objective by linking the design processes and stages across the disciplines (A. Qureshi et al., 2013).

This empirical study was designed to develop and clarify these links so that they could be organized into the first year design course. The study consisted of 34 individual interviews with the professors and academic leadership representatives from eight engineering disciplines: Chemical Engineering, Mechanical Engineering, Civil Engineering, Petroleum Engineering, Mining Engineering, Materials Engineering, Electrical and Computer Engineering,. Each interview consisted of three sections: a written questionnaire; an open-ended questions section; and a cognitive game task. The written questionnaire was focused on the design relevance of the participant's current course and the importance, in that course, of the fundamental elements of the proposed transdisciplinary engineering design course. The open-ended questions section was focused on engineering design and the discipline-specific design processes as well as their stages. The cognitive game task was developed from a stage-wise engineering design process (K. T. Ulrich & Eppinger, 2011), combined with Bloom's Taxonomy (David R. Krathwohl, 2010). It was designed for the following objectives:

1) To map the stage-wise discipline specific design processes on to a common engineering design process.

2) To collect the most commonly used engineering related nouns from each discipline.

3) To see the distribution of nouns across design stages; 4) To see the distribution of nouns and the related design activities across cognitive domains.

This paper is based on the last three goals of the cognitive game task, i.e., to collect the most generic engineering related nouns and to analyze their distribution. The nouns form the basis of Transdisciplinary Engineering Design Education Ontology (TEDEO), which, based on the semantics, connects the design concepts across the disciplines. The development activities of TEDEO are described in section 3.3. These semantic links are verified through Natural Language Processing (NLP) techniques / computational measurements along with SUMO. The links thus created are used to describe the distribution of concepts common to the different design processes and their stages, as well as Bloom's cognitive domains of learning. The results presented in this paper indicate the existence of a common engineering design process, across all engineering disciplines included in this study.

The paper is divided into three sections. First, it reviews the literature on ontology and describe the complete Transdisciplinary Engineering Design Education Ontology

(TEDEO). Next, the various NLP methods are explained that were used to create hypernym trees of the nouns based on semantics and the distribution of nouns across the cognitive domains of Bloom's Taxonomy. In the end, it describes the results obtained after applying the computational measures with a concluding discussion.

3.2. What is an ontology?

A lot of research has been conducted on what an ontology is and how can it overcome the terminology barrier across engineering disciplines. Ontology is a term taken from philosophy, which means "Theory of Existence" (Gruber, 1993; Mizoguchi & Ikeda, 1998). Neches (Neches R. Fikes RE. & WR., 1991) defined an Ontology as: "An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary".

As defined by Gruber, in engineering an ontology is "an explicit specification of conceptualization" (Gruber, 1993). That is, an ontology is an abstract model of some real phenomenon whose concepts and terms are identified and defined explicitly (Štorga et al., 2010). Because relations and concepts are explicitly defined according to views of a certain group of people, Guarino and Giaretta proposed a modified definition as "An explicit partial account of conceptualization" (Guarino, 1995).

Ontologies are always extracted from a set knowledge base. An ontology provides the means for describing explicitly the conceptualization in a knowledge base (Corcho, Fernández-López, & Gómez-Pérez, 2003). Uschold and Jasper (Uschold & Jasper, 1999) argue further that an ontology includes not only definitions, but also "an indication of how concepts are inter-related which collectively impose a structure on the domain and constrain the possible interpretations of terms." Ontologies are written in a very precise and formal way by clearly defining the axioms and concepts in a constrained manner (Storga et al., 2005).

3.2.1. Classification of Ontology

There are different classes of ontologies based on the level of dependence, the ontology extraction approach and the degree of formality. The level of dependence is specific to the ontology building concepts which, are accepted by a group of people during its conceptualization (Guarino, 1997a). For example, in top-level ontology, concepts are defined irrespective of an area of knowledge or application. Therefore it can be easily understood by a large group of people thus, making it the most generalized form of ontology.

The ontology extraction approach is the method that determines "*the scope of knowledge initially required*" to start building the ontology (Corcho et al., 2003). For example, in a top-down approach, the *generalized* concepts are first identified and later *specialized* to finish the ontology.

The third class is based on the language that is used to specify the concepts of an ontology (Uschold, 1996a). For example, an informal or semi-informal ontology is defined using day-to-day terminologies. Unlike formal ontologies, these can be easily understood despite the type of knowledge it contains. Below is the description of each class of ontology. The classes and categories of Ontologies are shown in

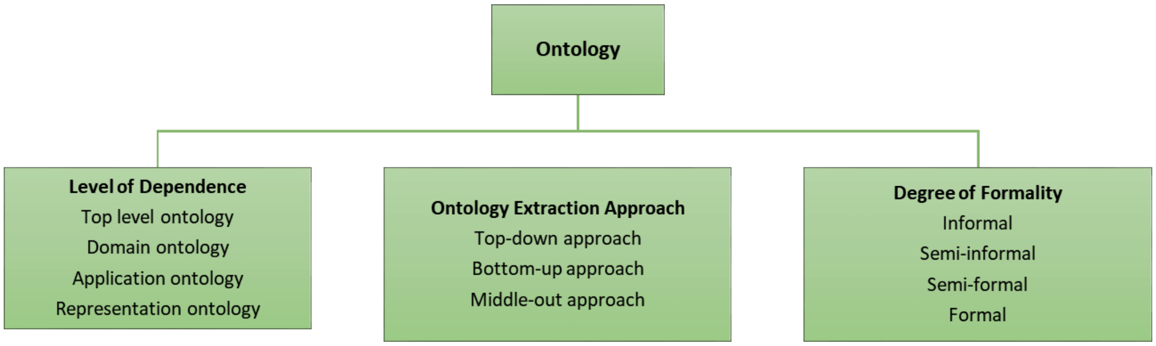

Figure 7 and are described below.

3.2.1.1. Level of dependence

Based on the level of dependence, (Guarino, 1997b, 1998) described following categories of Ontologies:

a) *Top-level ontology*: The top-level ontology is general and independent of any domain, application or knowledge community. This is also called upper level ontology (Štorga et al., 2010). CYC and SUMO are examples of Upper level or epistemological, ontology.

b) *Domain ontology*: Domain ontologies are built for particular domains and contain the knowledge base and axioms of that domain. It is a generic ontology at the domain level but specializes the terms. For example, KACTUS (Schreiber, Wielinga, & Jansweijer, 1995) was developed to build domain ontologies.

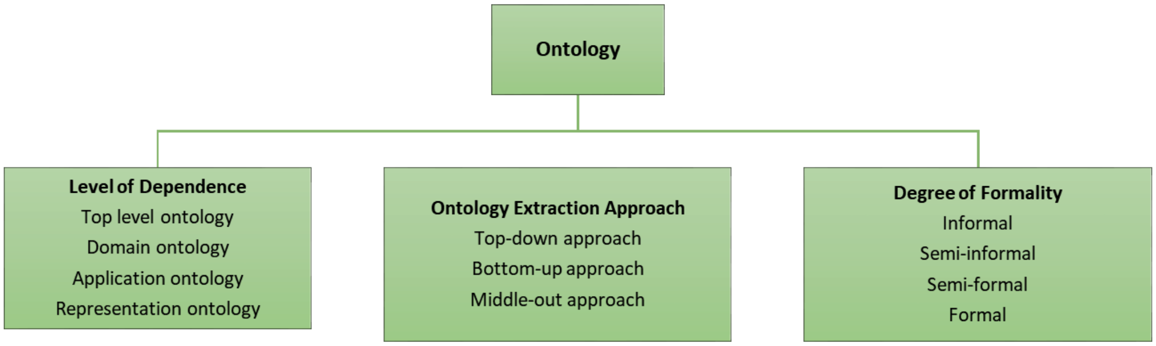

Figure 7 Classification & categorization of ontology

c) *Application ontology*: An application ontology is built for a particular application within a domain and contains entities only for that particular application.

d) *Representation ontology*: The representation ontology is neutral with respect to defining entities (Guarino, 1997b). It provides primitive system to describe other ontologies such as domain or generic ontologies and it is easily compatible with multiple representation languages. These are convertible and easy to translate from one system to another and are applicable across knowledge communities. The Frame Ontology, used in Ontolingua is one example (Gruber, 1993).

3.2.1.2. Ontology extraction approach

The following extraction methods may be used (Corcho et al., 2003):

a) *Top-down approach*: In this approach, a *general* abstract set of concepts is identified. The ontology gradually becomes rich and more specific by further categorizing the concepts into multiple specialized categories. E.g. the SENSUS method described by Gopez (Corcho et al., 2003) is a top-down approach built for domain Ontologies.

b) *Bottom-up approach*: In this approach, the *specialized* concepts are first identified, and then later generalized. E.g. the EDIT ontology was made this way (Ahmed, Kim, & Wallace, 2007).

c) *Middle-out approach*: In this approach, the most *important* concepts are first identified, and then later generalized and specialized into other concepts. The enterprise Ontology was created in this way (Uschold, 1996a).

3.2.1.3. Degree of formality

The degree of formality determines the language for coding the Ontology. Based on the degree of formality, an ontology is categorized into following types (Uschold, 1996a):

a) *Highly informal*: This ontology is expressed loosely in natural language as in enterprise ontology.

b) *Semi-informal*: This ontology, also called structured informal ontology, is expressed in a restricted and structured form of natural language. Compared to informal ontology, it increases clarity by reducing ambiguity.

c) *Semi-formal*: This ontology is expressed in an artificial, formally-defined language (a code), for example the Ontolingua version of the Enterprise Ontology (Uschold, 1996b).

d) *Formal*: This ontology defines terms in detail, using formal semantics, theorems and proofs of these properties for soundness and completeness. Formal ontology deals with both knowledge acquisition and knowledge representation (Guarino, 1995; Uschold, 1996b).

3.3. Overview and development of TEDEO

Transdisciplinary Engineering Design Education Ontology (TEDEO) is a top-level ontology following a bottom-up approach. In order to create TEDEO, a diverse array of nouns was restructured, through extrinsic definitions, to form semantic links between them. In (Butt et al., 2018) the TEDEO development activities were presented only for the first engineering design stage. This paper presents the development activities for all the six stages of the engineering design process, based on the following hypothesis:

> "*The major engineering disciplines teach a common engineering design process to students, irrespective of the terminology and the nature of the product.*"

The process of building TEDEO consisted of management, development and maintenance activities. Below section describes the development activities of TEDEO, which include the following stages: data collection, terminology identification, categorization, Validation and formalization, and implementation.

The phases of development activities are given in Figure 8 and Figure 3. The following text describes each stage:

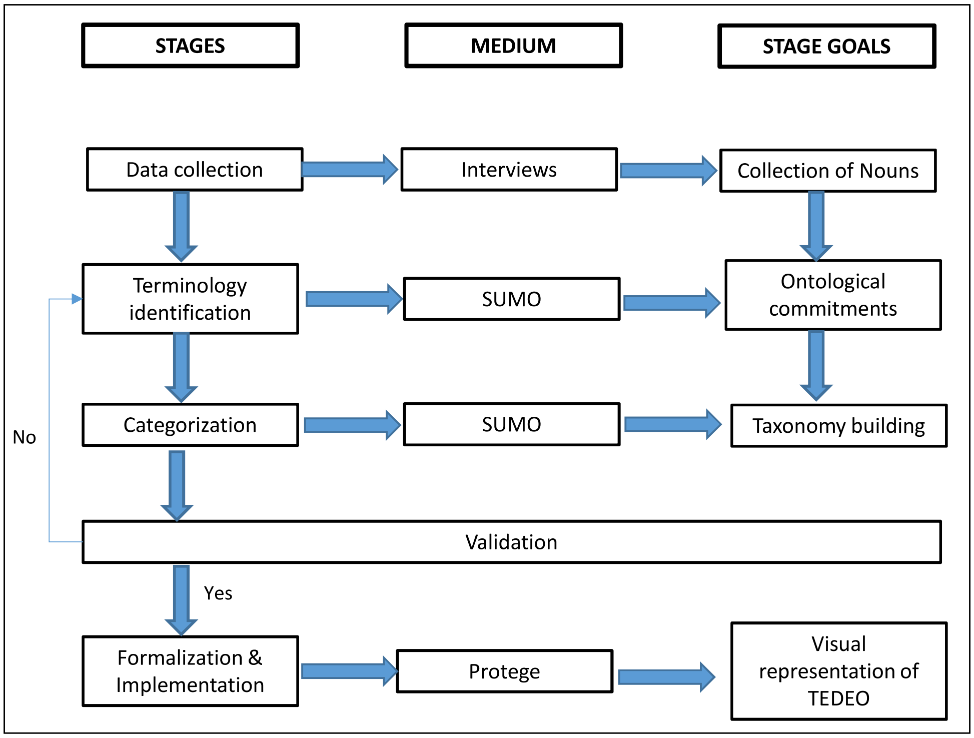

Figure 8 TEDEO development activities

3.3.1. Data collection

The data collection stage consisted of 34, one-hour long, individual interviews with professors and academic leadership representatives in the Faculty of Engineering, University of Alberta. The data for the current analysis was collected during the *cognitive game* part of the interview. For this task, all participants were proposed a common six stage engineering design process consisting: *planning, concept development, system-level design, detail design, implementation and testing; and final production* (K. T. Ulrich & Eppinger, 2011). Participants were asked to reorder and/ rename the design stages according to their disciplines. Then, each of them was given a set of 42 verbs; 7 verbs from each of the six levels of Bloom's cognitive domains (David R. Krathwohl, 2010). Participants were asked to write at least one engineering related noun against each verb, forming a verb-noun pair. One out of 34 participants did not propose any nouns against the verbs thereby reducing the number of verb-noun pair by 42. Each pair was considered as a design activity. Finally, all participants were asked to place this activity, as they understood it, under one of the six stages of the proposed design process. The details of the interviews are given in (Butt et al., 2018; Sharunova et al., 2018).

At the end of this game, a total of 1611 individual nouns and verbs were collected. A total of 1566 design activities were collected, 45 less than an ideal number of 1611. Because while collecting the design activities, 45 verbs were found without a noun, thereby, reducing an ideal number of 1611 activities to 1566. The distribution of design activities across six design stages was analyzed in two parts.

a) Verbs: A total count of 1427 verbs was made from 1566 design activities i.e., 42 verbs for each of the 34 participants. The verbs were analyzed to see the distribution and application of Bloom's Taxonomy during the engineering design process. A complete analysis of verbs is done by (Sharunova et al., 2018).

b) Nouns: A total of 1611 nouns were collected. The nouns were diverse and distributed across six design stages of eight engineering disciplines. As reported by participants, their selection of nouns primarily came from their teaching experience followed by their research or professional experience (Sharunova et al., n.d.). Table 2 shows the distribution of nouns irrespective of the disciplines. The nouns were analyzed to make a unique list of 321 nouns.

   The final list was based on the following filtration:

   - There was no repetition of nouns within and across the design stages or engineering disciplines.

- The nouns were reduced to their infinitive form.

Stages	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6
Raw number	263	369	274	292	299	114
Unique nouns in each design stage	101	130	113	119	120	70
Unique nouns across all design stages	321					

Table 2 Distribution of nouns across six design stages

3.3.2. Terminology identification

To identify the explicit meaning of 321 nouns, generalized engineering-related definitions were carefully chosen using Suggested Upper Merged Ontology (SUMO) (http://www.adampease.org/OP/). SUMO is a formal ontology which is comprised of several generalized definitions for the universal concepts from a broad range of different domain areas. SUMO was created by merging publicly available ontological data into one fully structured and comprehensive database (Niles & Pease, 2001). SUMO, mapped on WordNet (Pease & Fellbaum, 2010), is an upper level ontology with meta-level concepts that were expanded to include Mid-Level Ontologies (MILO) and dozens of domain Ontologies.

3.1.1. Categorization

The nouns were categorized using SUMO as per the procedure and hierarchy given in (Butt et al., 2018; Štorga et al., 2010; Storga et al., 2005). The categorization was based on the definitions assigned to each entity. The nouns were categorized into two major classes, Physical and Abstract, and six sub classes Object, Process, Attribute, Proposition, Quantity and Relation, respectively. The detailed class structure of Physical and Abstract quantities is given in Figure 4. The detailed description of each class is available at (http://www.adampease.org/OP/).

3.1.2. Validation

The validation of entities was done by measuring the inter-rater reliability through Cohen's Kappa co-efficient (Harwood & Garry, 2001). Primary researcher and the design expert analyzed the definitions and categorized the same terms independently. The results were compared to measure the reliability. The Kappa coefficient was calculated for both major and sub-categories. The value of coefficient was 0.53 for top-level classes while 0.52 for the sub-classes. According to the range of Cohen's Kappa co-efficient, on a scale of 0 (minimum) to 1(maximum), a value between 0.41 and 0.6 shows "moderate agreement". To improve the value of Kappa co-efficient, the definitions and categorizations were revisited. The value of Kappa coefficient was recalculated as 0.85 for the two top-level classes and 0.84 for the six sub-classes. According to the range of Cohen's Kappa co-efficient, a value between 0.81 and 0.99 shows a "near to perfect agreement".

The resulting division of entities into two major and six sub-categories is shown in Figure 9. During the validation process, some entities were rendered as "*un-defined*". The undefined entities were those, which could not be categorized exclusively as either Physical or Abstract. For example, "things" was categorized as "Physical" by primary researcher and as an "Entity" by the validator. Which means, it can be a Physical as well as an Abstract quantity. The percentage agreement between researchers is shown below.

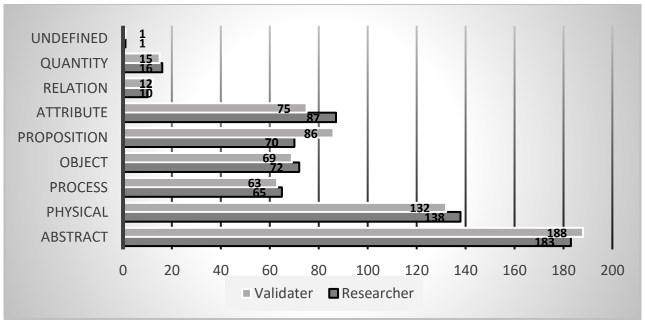

Figure 9 Number of entities in each category

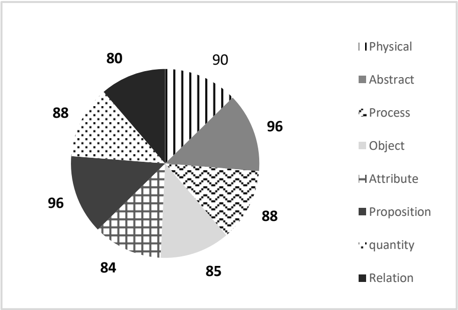

Figure 10 Percentage agreement

3.1.3. Formalization and implementation

Once the entities were categorized and validated, Protégé (https://protege.stanford.edu/), an open-source free software was used to build the Taxonomy of entities in the form of subclasses and classes. Protégé provides a framework to build a network of knowledge base. It provides tools to its users for creating Ontologies by defining the properties and the relations between entities. Further, its visualization tools OwlViz and OntoGraf enable users to visualize their ontology. The output from OntoGraf is a ".dot" file that can be imported into GraphViz to visualize a fine structured ontology. Figure 11 is a GraphViz output image. Once the 321 entities were validated they were assigned back to their respective disciplines and design stages to show the accurate representation of data from each discipline. This provided a list of nouns for each design stage that was unique for each discipline i.e., there was no repetition of nouns within the same discipline.

After forming the subclasses and classes in Protégé, they were filled with relevant nouns i.e., entities. The next step was to use the *property function* of Protégé to relate those subclasses with classes and their meta-classes. Figure 11 demonstrates very simple concepts. The individuals at the bottom are part of relevant sub-classes. The sub-classes are related to other classes and their meta-classes via properties such as, IsClassifiedInto, IsCategorizedInto4 etc. Appendix A.5. shows complete TEDEO for all the six stages of design process.

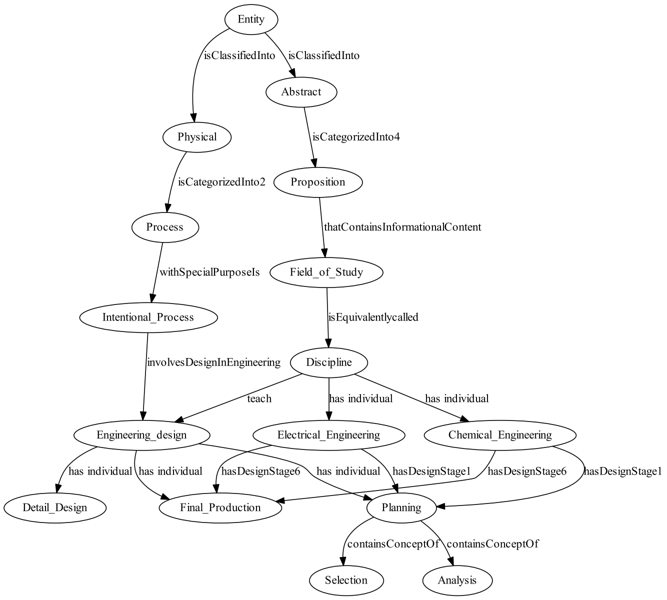

Figure 11 Visualization in GraphViz

3.2. Semantic similarity by using Natural Language Processing (NLP)

Natural Language Processing (NLP) techniques were used to validate the semantic links based on the nature of the data collected through the cognitive game. The nouns were used in combination with NLP techniques to create trees of hypernyms for each individual stage. A hypernym is defined as the more generalized form of a word. WordNet (https:/wordnet.princeton.edu/) defines hypernym as “A word that is more generic than the given word” (Taylor, Poliakov, & Mazlack, 2005) describes hypernym of noun as “Y is a hypernym of X, if every X is a (kind of) Y”. E.g., “compressor” and “lathe” are special types of a general category of “machine”, where machine is the hypernym of both compressor and lathe. The NLP techniques processed all nouns of the same hypernym, thereby semantically connecting similar concepts at an abstract level, irrespective of the discipline. The result was a tree-like structure as shown in Figure 12 and explained in section 3.3. A literature review on NLP is given below.

3.2.1. What is Natural Language Processing?

Natural Language Processing, also called computational linguistics, is the research field of linguistic analysis, which uses computational technique to process human language content (Woolley, 2011). The linguistic analysis is divided into various levels (Liddy, 2005). This study reviews only the semantic level of NLP techniques, which measures the semantic similarity between any two concepts and creates a significant relation between them. The semantic similarity between any two concepts is determined directly by the degree of their commonalities and inversely by the degree of their differences. Semantic similarity can be measured using different parameters called "building blocks" (Li, Bandar, & McLean, 2003) or "categorization" (Slimani, 2013).

The initial work on similarity measures was divided into distance based similarity; also called edge based approach and information based similarity; also called node-based approach (Mc Hale, 1998). The distance based similarity measures were based on edge counting, where all the edges were assumed to be of equal length. The less is the count of edges between any two words in a Taxonomy, the more closely they were related (Rada, Mili, Bicknell, & Blettner, 1989). The results of edge counting were compared and improved by Resnik (Resnik, 1995, 1999), who defined similarities between any two concepts as the maximum information content of a concept, which subsumes both of them in the Taxonomy.

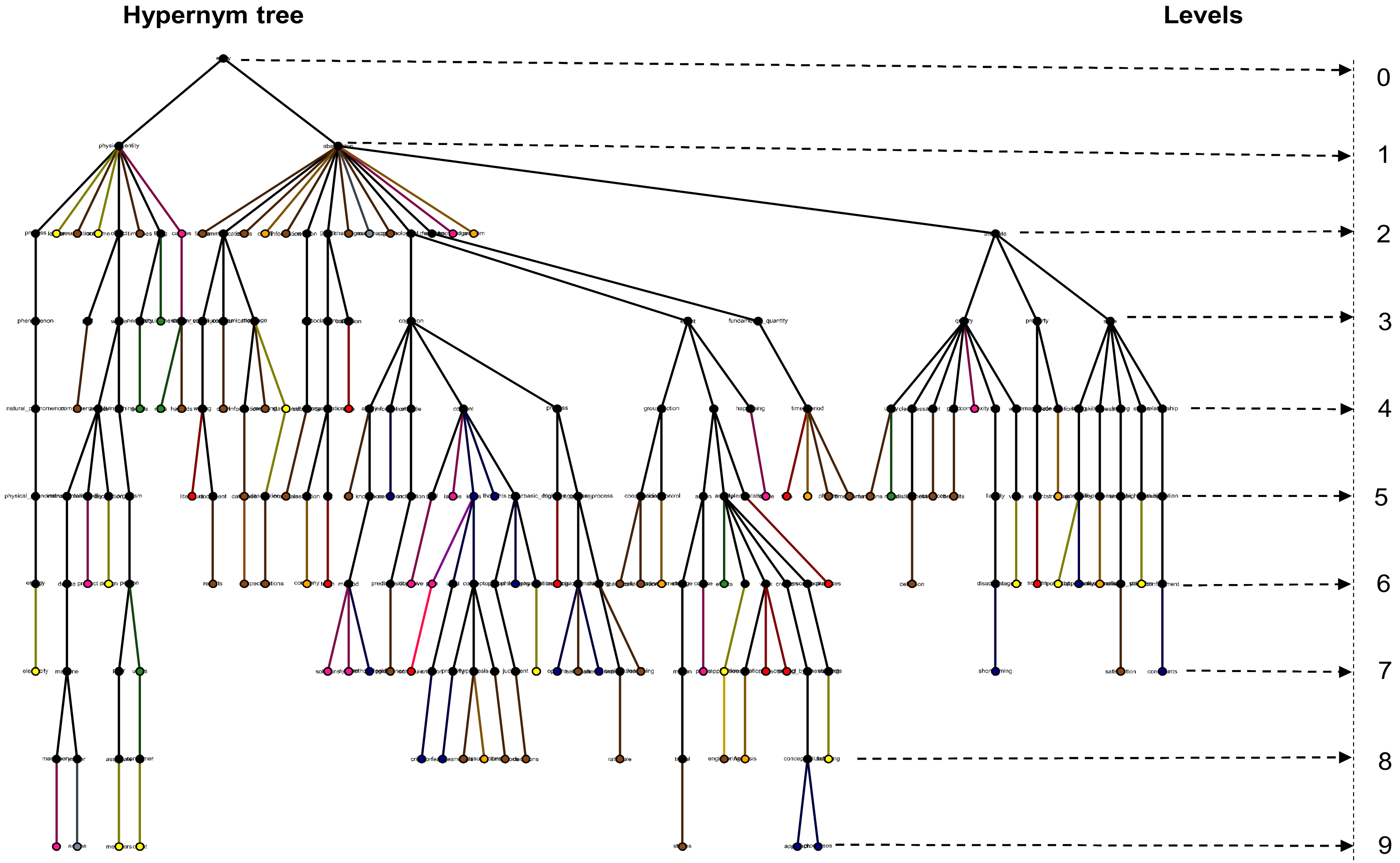

Figure 12 Hypernym tree for first design stage

Some authors combined both distance based and information-based approaches to enhance the results. They presented a hybrid approach to measure semantic similarity. Jiang and Conrath (Jiang & Conrath, 1997) measured similarity between two concepts, C1 and C2, based on the amount of information they share. This shared information is defined by the nearest parent node C, called the super class of concepts C1 and C2, which subsumes both the concepts in a hierarchy. Richardson and Smeaton (Richardson & Smeaton, 1995) used WordNet as the knowledge base to define and control vocabulary and derived the information-based and conceptual distance-based semantic similarity functions to compare words. Other authors presented similar approaches (Jiang & Conrath, 1997; Leacock & Chodorow, 1998). In order to ensure accuracy, this study applied computational techniques derived from each of the three approaches. These techniques are the edge based approach i.e., Wu and Palmer method (Wu & Palmer, 1994), the node-based approach i.e., Lin approach (Lin, 1998) and the hybrid approach i.e., Jiang and Conrath method (Jiang & Conrath, 1997) and Leacock and Chodorrow approach (Leacock & Chodorow, 1998).

3.2.2. Parsing, POS tagging and lemmatization

The other NLP techniques used to conduct this part of research include parsing, POS tagging and lemmatization. Parsing (Berant & Liang, 2014) is a kind of linguistic pre-processing technique, which produces a full parse tree of the text. Parsing can be used to find the relation between words in a sentence (Hotho, Andreas, Paaß, & Augustin, 2005). A few of the many parsing approaches include Parasempre (Berant & Liang, 2014), SPATTER (Magerman, 1995) and the dependency parser (Björkelund, Bohnet, Hafdell, & Nugues, 2010). POS tagging (Jurafsky, 2000) is also one of the linguistic pre-processing steps that assigns syntactic categories to words in the sentence i.e., it tags whether a word is a noun, verb, or adjective etc. POS tagging is helpful in giving information about the nature of the word e.g., named entities in a document like people or organizations. Lemmatization is one of the most important components of computational linguistic applications (Straková, Straka, & Hajič, 2014). It is the process of finding the normalized form of a word by reducing the word into its root form. (Plisson, Lavrac, & Mladenić, 2004) defines lemmatization as a "replacement of a suffix (the grammatical ending) by another suffix (the ending of the normalized word)". Various open source lemmatization tools are available such as Morphdita (Straková et al., 2014), MorphAdorner (MorphAdorner) and Morphy (morphy) which is a word net tool (Fellbaum, 1998; Miller, Beckwith, Fellbaum, Gross, & Miller, 1990).

3.2.3. Methodology

The following steps were taken to create hypernym trees of nouns in each stage. A systematic layout is shown in Figure 13.

1. The XLSX input files were parsed by a Python library called **Pandas** (https://pandas.pydata.org/). Once done, the information was stored in a python dictionary. Every noun was related to a verb, a department, a Sumo Id and its nature (Physical / Abstract). Some entities, that could not be found in SUMO, were categorized based on WordNet and therefore they were not assigned a SUMO Id.

2. The active nouns were lemmatized and white spaces and noise were removed from the ".xlsx" document. The lemmatization was done using the WordNet lemmatizer tool, morphy (morphy) inside the Natural Language Toolkit library (https://www.nltk.org/). NLTK has an interface to WordNet; therefore, it has

functions that can access and use WordNet lexical database and algorithms. NLTK's interface was used to access WordNet's lemmatization tool.

3. While using the **py4j** library (https://www.py4j.org/index.html), the Python code sent the information to the Java Virtual Machine (JVM), running locally on the computer. When received, the Java program used the development environment called SigmaKEE (http://Ontologyportal.github.io/sigmakee/), as a JAVA library and a tool for developing and viewing theories in first order logic, to interact with SUMO. It then traced the hypernyms of the collected nouns. The result was a hypernym graph in which all the nouns were connected to their hypernyms. In cases, where an entity had more than one hypernym, the code performed a comparison to choose a hypernym that was semantically more similar to the noun. The comparison was done using the WordNet Similarity for the JAVA (WS4J) Library, which computed the average of four semantic measures.
4. To create the graph output files, each department was assigned a unique color. The color coding is given in Table 3. All the information about nouns (i.e. the color, the synset and the design stage), hypernyms (the noun and the synset) and their edges was stored as a ".gdf" file. In the next step, the Python script was executed to read ".xlsx" and generate the data in the form of bar plots.
5. The ".gdf" file, generated after python execution, was loaded into Gephi. GraphViz layout (https://www.graphviz.org/theory/) was selected to visualize the results in the form of a tree-like structure.

Department	Colour
Mechanical	Red
Electrical	Orange
Chemical	Blue
Civil	Green
Petroleum	Grey
Computer	Yellow
Mining	Pink

Table 3 Colour coding

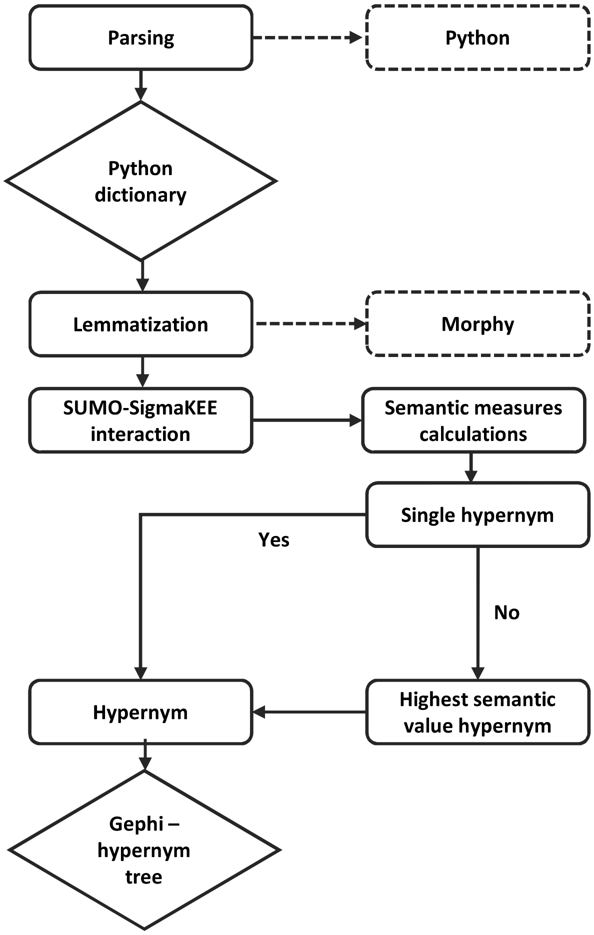

Figure 13 Graphical layout of hypernym tree formation

3.3. Results and discussion

3.3.1. Hypernym tree

A complete hypernym tree for the first design stage is shown in Figure 12. Six hypernym trees were created, one for each design stage. As the figure depicts, each tree is divided into multiple levels; 0 is the top most level (entity) and “X” is the lowest level (X is 9 for 1st, 10 for 2nd, 11 for 3rd, 10 for 4th, 11 for 5th and 12 for 6th design stage). The number of levels were identified based on the information content carried by the proposed nouns and as suggested by SUMO. Each parent level of the tree is a hypernym of its child and is represented in the form of a black colour node[1]. E.g., the top node at level 0 is called “Entity”, which is the hypernym of its two child-nodes “Physical” and “Abstract” at level 1. This parent-child hypernym relation continues until the bottom nodes of the tree, which represent the nouns proposed by the participants. The level of each noun in a tree is a function of its knowledge depth; all the nouns proposed by the participants belong to a different level of the tree. The lower the level of the noun (“0” being the highest), the more specialized the information about a concept it contains. In other words, the more a concept merges with similar concepts in the hypernym tree, the more generalized meaning it attains and vice versa.

In addition to the tree, a simple noun frequency count was done, based on the number of nouns attached to each of the two hypernyms at level 1, irrespective of disciplines. This activity reported a total of 145 “Physical” and 508 “Abstract” entities. The counting was repeated for each design stage. Figure 14 shows the division of entities into each of the

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[1] In case, one noun from interview is a hypernym of another noun from the interview, its node is not black, although it still completes the tree as a hypernym.

categories. An analysis of this division depicts how discipline experts in engineering tend to think of the design activities. A higher number of abstract concepts indicates that the design knowledge delivered to the students is centered more towards "concepts" of things e.g., *ideas*, a kind of entity, which describes the concept or physical existence of a thing, but it, is not physical itself. Similarly, *management* does not has a physical existence but it teaches how to manage physical entities. Some examples of these abstract concepts are *objectives, assumptions, interactions,* and *approach*. The trend favors the explanation that the experts' thinking while describing the activities was guided by the nature of design knowledge they teach to the students; they teach a conceptual understanding of the design process. This conceptual understanding of design helps graduates in building the physical models and products later in their professional careers.

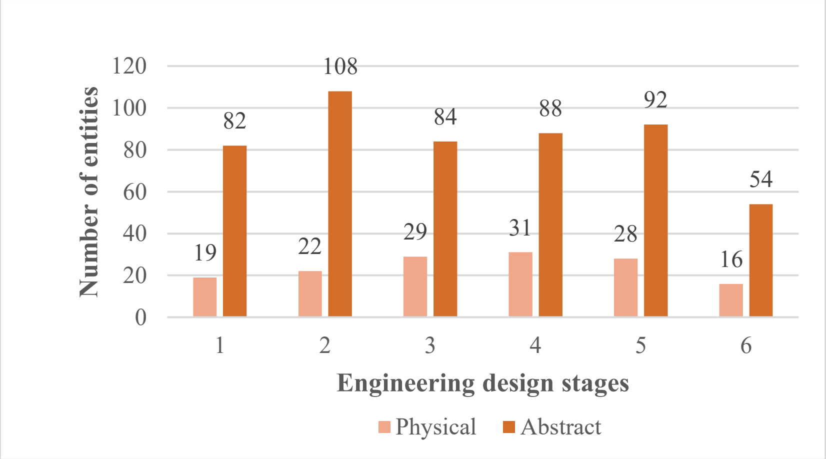

Figure 14 Physical and abstract entities

3.3.2. Distribution of entities across Bloom's domain for six-stage engineering design process

To see how the core concepts of engineering design in each design stage are distributed across six cognitive levels of Bloom's Taxonomy, the complete engineering activities (verb-noun pairs) of each design stage, were traced at level 1 of hypernym tree. The hypernyms “Physical” and “Abstract” at level 1 subsume all those nouns which are in a parent-child relationship as described previously. The verb from each pair was used as a bridge to put the nouns under each of the cognitive domains. For instance, the hypernym “Physical” is attached to all the verbs that form a pair with the nouns subsumed by “Physical”. The verbs from each cognitive domain are counted to see how many of the nouns belong to that domain. The same activity is performed for each design stage. Figure 15 and Figure 16 show the relation between design concepts, design stages and the cognitive domains.

The analysis helps in understanding the following: 1) how the design concepts link to Bloom’s Taxonomy; 2) which physical or abstract concepts are most *commonly occurring* at each stage of engineering design process.

Figure 15 shows the distribution of design concepts across Bloom’s cognitive domains which are *knowledge (kn), comprehension (cm), application (ap), analysis (an), synthesis (sn) and evaluation (ev)* (David R. Krathwohl, 2010; Narayanan & Adithan, 2015). The graph shows the highest peaks for abstract and physical quantities at knowledge and synthesis domains, respectively. It means that the abstract quantities have highest occurrence at first cognitive level. Because this is the first domain of learning, therefore, it contains highest number of abstract nouns that deliver the conceptual *knowledge,* such as knowledge of terminologies, methodologies, principles etc. The peak keeps reducing as the cognitive level increases, justified by the fact that higher amount of initial level knowledge is required in each preceding domain to shape the rest of information/physical outputs in proceeding domains (David R. Krathwohl, 2010).

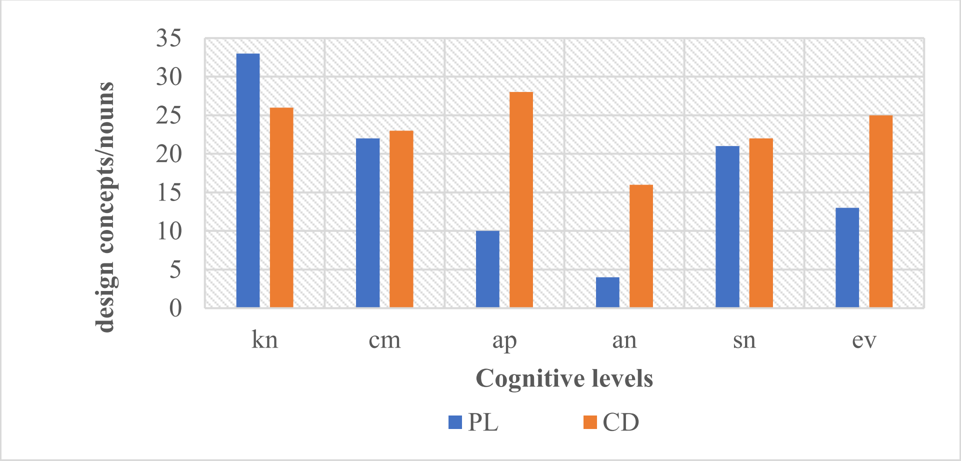

Figure 15 Distribution of design concepts across Bloom's cognitive levels

However, the peak again starts increasing from synthesis domain because at this level, all the previous concepts, whether learnt or applied, are combined to give finalize the output. In evaluation domain, the number of abstract nouns are almost equal to those in knowledge domain. This domain particularly evaluates the concepts that were applied, analyzed and synthesized during the process. Therefore, it shows cumulative evaluation of concepts related to knowledge, information and result of application.

Similarly, physical entities show highest count in synthesis domain because this domain implements previous understanding of both physical and abstract entities and gives a physical form to the objective. It is to be noted that the term physical does not only means the physical form of the product, but it means the completeness of the problem objective. The other peaks, low in number show that the abstract knowledge at these stages was much higher because it was used to build smaller parts of tangible outputs, which are later combined at the synthesis level to produce the real output.

The graph also shows an interesting division of design concepts taught to the students. The distribution shows that a greater number belongs to the first three levels of cognitive thinking which supports students in using complex higher levels of thinking at a later stage of their professional career. Section 3.3.3 confirms the same.

Figure 16, showing the occurrences of design concepts at each stage of the process. It is clear from the chart that all cognitive domains perform a significant part at each stage of the process. However, on average, the first three levels of cognitive domains tend to dominate, except the final production stage, where the evaluation domain is the most prominent. In addition, knowledge has the highest peak at all design stages, except the detail design and the production stage. It is because of the nature of activities which are focused towards shaping the final product.

Below is a discussion on the stage-wise distribution of design concepts, which shows that the nature of information changes at every stage, thereby, changing the effective cognitive domains. For example, the nature of information at first stage of the process is preliminary which keeps on getting precise and refined as the process enters the later stages.

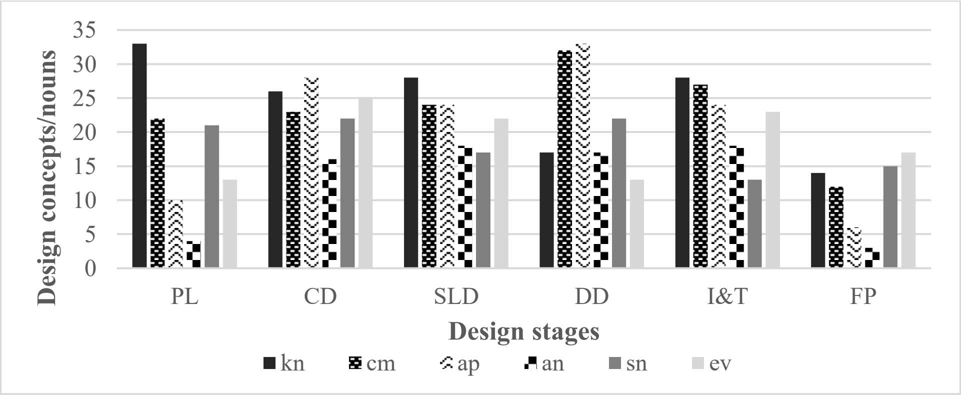

Figure 16 Distribution of design concepts with respect to Bloom's cognitive levels across engineering design process

1. Stage 1 of the design process shows a peak in concepts relevant to the *knowledge* domain. This is because all knowledge is gathered during the planning stage of the

process that carries out activities in other stages. Next, successful implementation of planning also includes the *comprehension* of the available information and then its *synthesis*. If knowledge about the problem is left incomplete at first stage, or data is *misunderstood*, or knowledge is not *synthesized* carefully, other stages cannot be executed. The rest of the three domains, despite having low peaks, are equally important to process and understand the information, as required. Some of the nouns suggested by participants in this stage are given below.

Stage 1	Approaches, options, risks, methodologies, opportunities, alternatives, constraints, literature, efforts, priorities, cost, resources, skill

2. Stage 2 of the design process demands the *understanding* and *development* of a problem concept; therefore, it utilizes significant levels from all the cognitive domains especially the *application* domain. At this stage, preliminary knowledge is in a more refined form. The *comprehension* domain, higher in value than previous stage, shows that the knowledge acquired during stage 1 is used to *comprehend* the project requirements and scope of work. Next, this information is applied to formulate a complete schedule of activities and design for future stages thus, giving highest peak to the *application* domain. The *evaluation* domain assesses the impact of decisions taken during 1st and 2nd stage and incorporates any suggestions to improve the later stages of product development. Some of the nouns proposed by participants in stage 2 are given below.

Stage 2	Techniques, practices, literature, results, schedule, scope, activity, codes, objective, knowledge, feasibility, relationship, variables

3. At stage 3, the nature of information is clear of any ambiguities. The *knowledge* domain again dominates, which means that the 3rd stage of the project requires overall knowledge of standards, regulations, limitations and other product design parameters, which must be taken care of during the detail design stage. Cognitive levels such as *comprehension* and *application* are utilized significantly to design systems and sub-systems. These systems are *evaluated* based on the output required. This is shown by the evaluation domain. Some of the nouns proposed by participants in stage 3 are given below.

Stage 3	Reactor, size, energy balance, efficiency, characterization, implementation, structure, suppliers, sub-system, statistics, mechanism, problems, function

4. Stage 4 shows dominating peaks at *comprehension* and *application* domains, which are precisely in line with the detail design requirements. At the detail design stage, designers *comprehend* the available parameters such as, reactor descriptions, material selection, and weight and *apply* them in a structured way to develop a detailed design of the product. The outputs include drawings, weight, product temperature, design algorithm, equation etc. The results thus obtained at the end of this process are combined together, shown by the *synthesis* peak, to make deliverables for the next stage of the process. This stage is also supported by *knowledge, analysis and evaluation* of given inputs, as depicted. Detail design stage is the only stage, after stage 1, with clear peaks of level 2 and 3. The remaining 4 levels are prominently lower because detail design stage is especially focused towards *understanding* and *development* details. Some of the nouns proposed by participants in stage 4 are given below.

Stage 4	Equipment, interactions, results, differences, loads, diagrams, details, values, selection, drawings, temperature, formula, forces, algorithms

5. Stage 5 requires *knowledge* of codes and standards to perform testing and validation of the detail design, shown by a peak of *knowledge* domain. On pragmatic grounds, any failure or unsatisfactory results during this stage may lead to change or refinement, which means a re-application of design that requires the *comprehension* of results and *application* of knowledge followed by re-evaluation, if required. Some of the nouns proposed by participants in stage 5 are given below.

Stage5	Efficiency, performance, data, model, challenges, finding, deformations, response, reliability, prototype, simulation, inspection, improvement

6. Unexpectedly, there was very less amount of data in stage 6. Participants while playing the game, claimed the absence of production stage in their design e.g., participants from civil and chemical departments who do not usually work with prototypes or equipment. The available data for Stage 6 shows high peak in *evaluation*, which means that the final report or product is reviewed for testing and client approval. All the deliverables at this stage are *synthesized*, and results are combined together to speed up project/problem closure, represented by next highest peak of *synthesis*. The lower cognitive domains do not play a significant role at the final stage, but they are still important to finish the process. Some of the nouns proposed by participants in stage 6 are given below.

Stage 6	Product, deadline, schedule, documentation, results, failure, drawings, operation, report, closure, material, expenditure, parts, evaluation

3.3.3. Distribution of design activities across Bloom's domains

The distribution of design activities across six cognitive domains of Bloom's Taxonomy is given in Figure 17. The vertical bars represent the number of design activities in each of the six domains. The graph shows maximum number of design activities were part of the lower cognitive domains. This implies the nature of design activities proposed by the design professors were part of the lower cognitive levels of Bloom's Taxonomy, mainly the knowledge domain. The distribution of activities in rest of the domains does not show a significant difference.

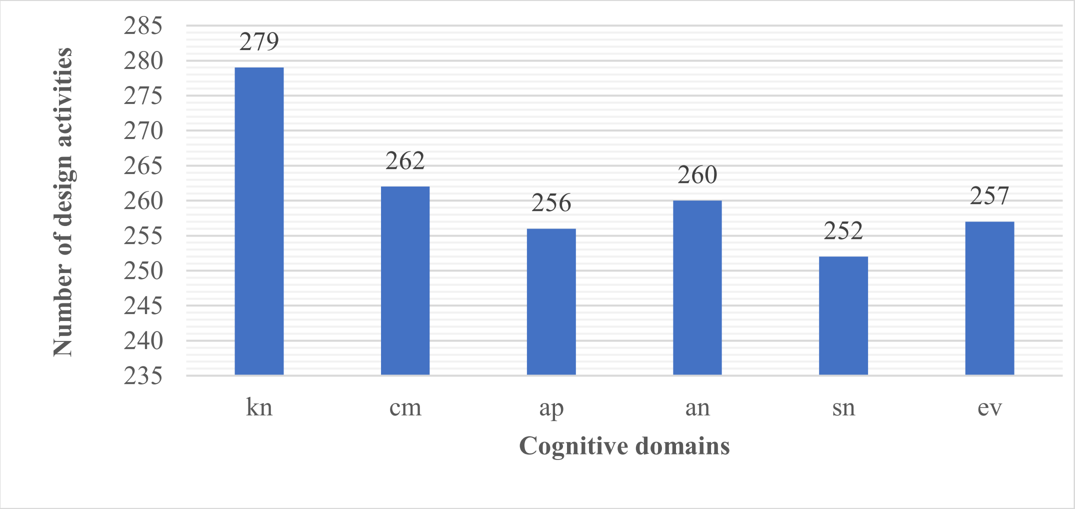

Figure 17 Distribution of design activities across cognitive domains

The tabular form of verb-noun combinations for all the 1566 activities is given in Appendix A.1. Figure 18 shows the same activities in graphical form. The pink circles represent the verbs, while nouns are shown as rectangles. Each verb shares multiple number of nouns thus, forming a network shown by fine blue lines. The graph was drawn in GraphViz (http://www.graphviz.org/) using “twopi”, which is a radial layout. GraphViz is an open source, graph visualization software, which enables its users to visualize data in the form of diagrams. The other possible layouts are hierarchical, spring, multiscale and circular layouts.

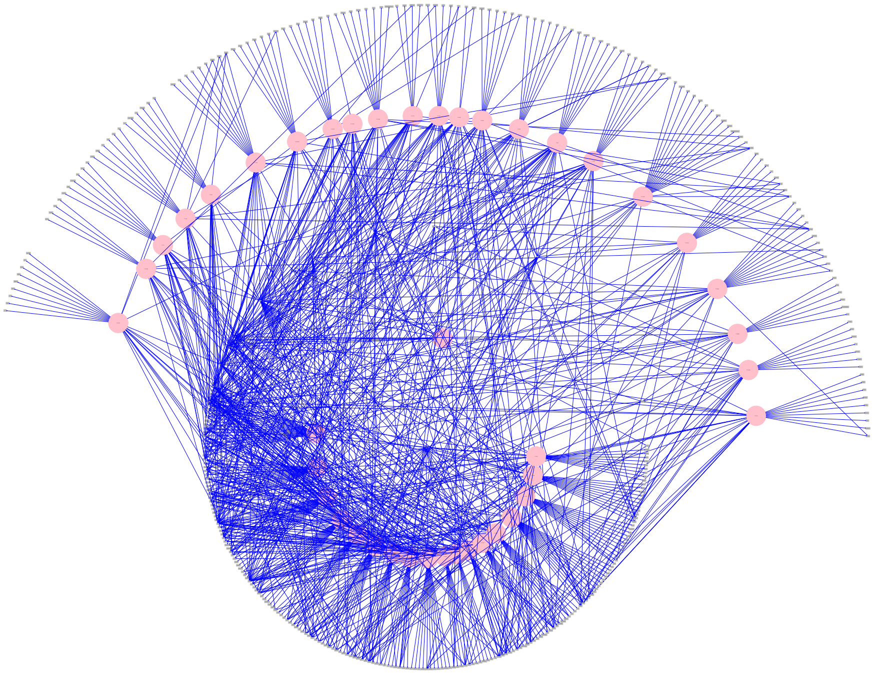

Figure 18 Design activities

Figure 19 shows the simplest depiction of verb-noun relations as well as the dependencies of verbs from different cognitive levels. Each circle represents a verb while a rectangle represents corresponding noun. Figure 19 shows that the understanding of design concepts is a stepwise procedure, which is distributed across the cognitive domains. In order to accomplish a design activity, a product must pass through a definite path of knowledge, comprehension, application, analysis, synthesis and evaluation. E.g., a “problem” cannot be *solved* unless it is *defined*. It means that, in order to achieve a certain level of product design, the design must proceed from a lower to a higher cognitive domain.

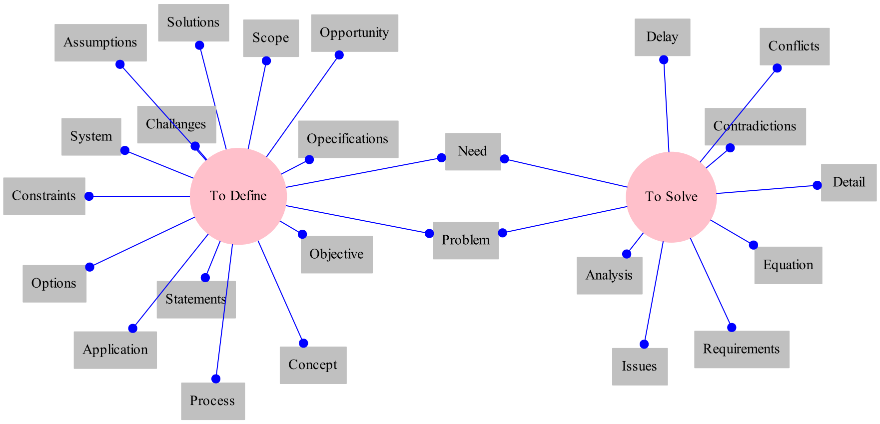

Figure 19 Mutual dependency of design activities

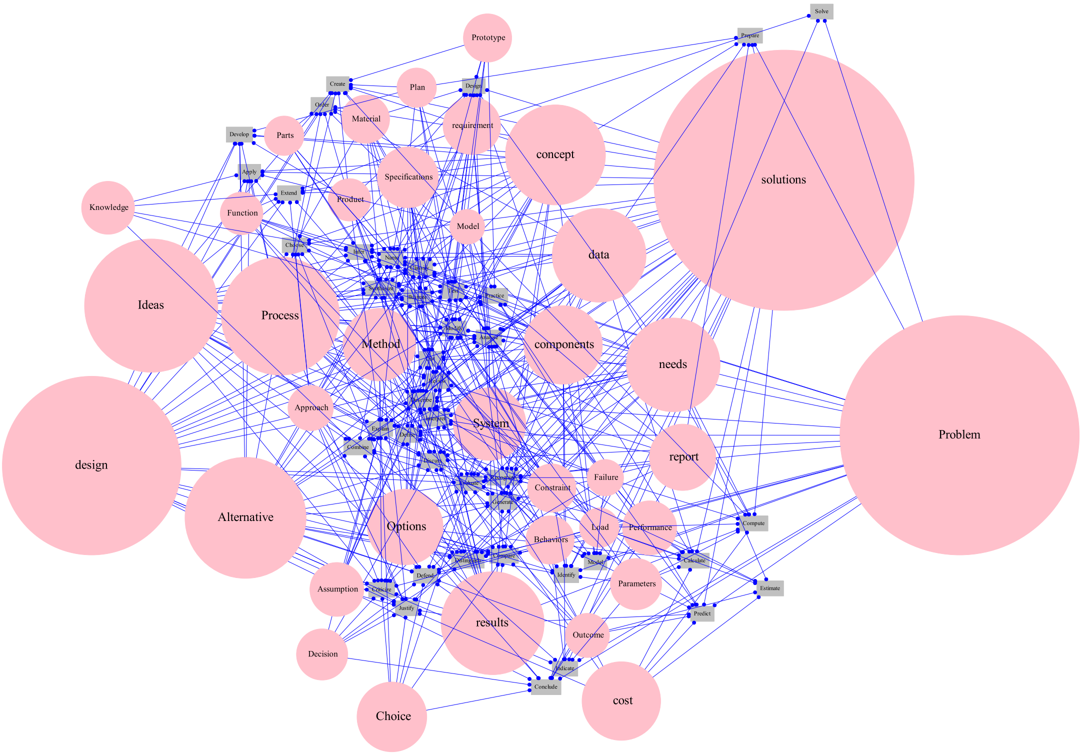

Figure 20 Design activities for selective nouns

Based on the frequency of noun usage, the unique list of 321 nouns was arranged in a descending order to count their frequencies. Appendix A.2. Noun frequencies table shows the frequency of each noun as used by the professors to form design activities. The highest frequency noun is “solution”, which is used 86 times to form a design activity. Similarly, problem was used 79 times; design 59 times etc. There were 144 nouns, out of 321 used just once. The distribution in Figure 21 depicts same information.

After that, all the nouns were arranged according to certain ranges, as given in Table 4. Each range representing the possible number of design activities formed with a noun. For example, there were 202 nouns, which made up 1 or 2 design activities. Similarly, there were 3 nouns, which paired up 51 to 90 times, with a verb to form a design activity. The range starts with a smaller number and widens progressively as the number of nouns starts decreasing.

Figure 22 represents same data in graphical form where the horizontal axis is representing the number of times each noun was used to form an activity. Analysis shows that the top three highest occurring nouns proposed as part of engineering design activities are *solution, problem and design*, used 86, 79 and 59 times, respectively. Some other nouns in the next highest range are *ideas, process, results, concepts, components* etc. It is noted that except *component*, all other highest occurring nouns in the top two ranges consist of abstract concepts.

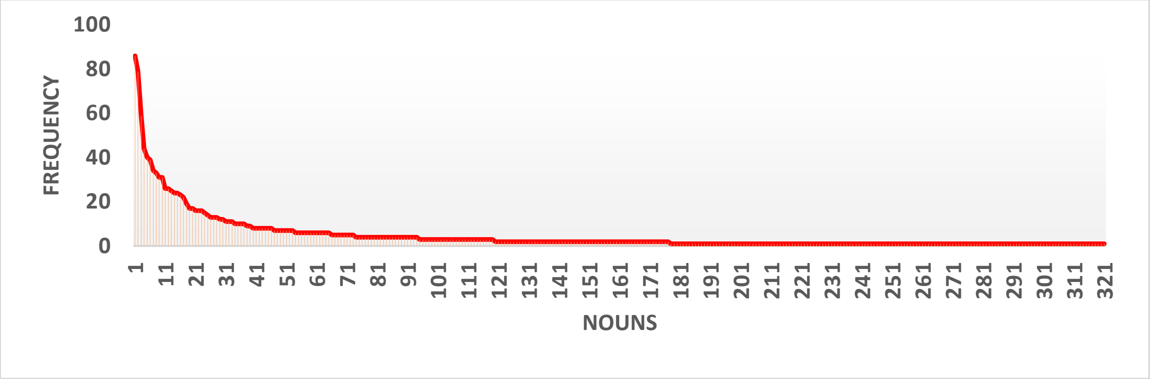

Figure 21 Frequency of noun usage

Number of Nouns	Range	
	Low	High
202	0	2
54	3	5
32	6	10
16	11	20
14	21	50
3	51	90

Table 4 Noun frequency range

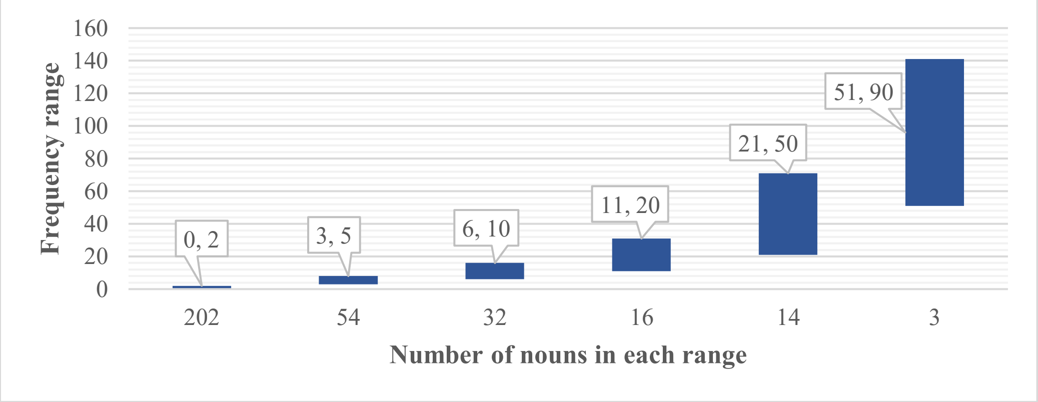

Figure 22 Noun frequency range

In addition to the individual analysis of nouns, a design activities table was formed to find noun frequencies against each verb. Appendix A.1 shows the complete verb-noun pairs, which were used to create Figure 23. The graph is divided into 42 sections which are equal to the number of verbs. Each section represents a set of design activities proposed by participants against a particular verb. The frequent peaks in each section represent the number of times a combination of verb-noun pair was used by the participants. For example, in section 1, the participants proposed “To define-problem” 18 times and therefore, it is the highest occurring activity in that section. Similarly, the activity “To solve – Problem” was used 26 times which is the highest occurring activity in that particular section. It can be seen in the graph that design activities pertaining to lower cognitive levels are showing high peaks compared to those in lower cognitive levels.

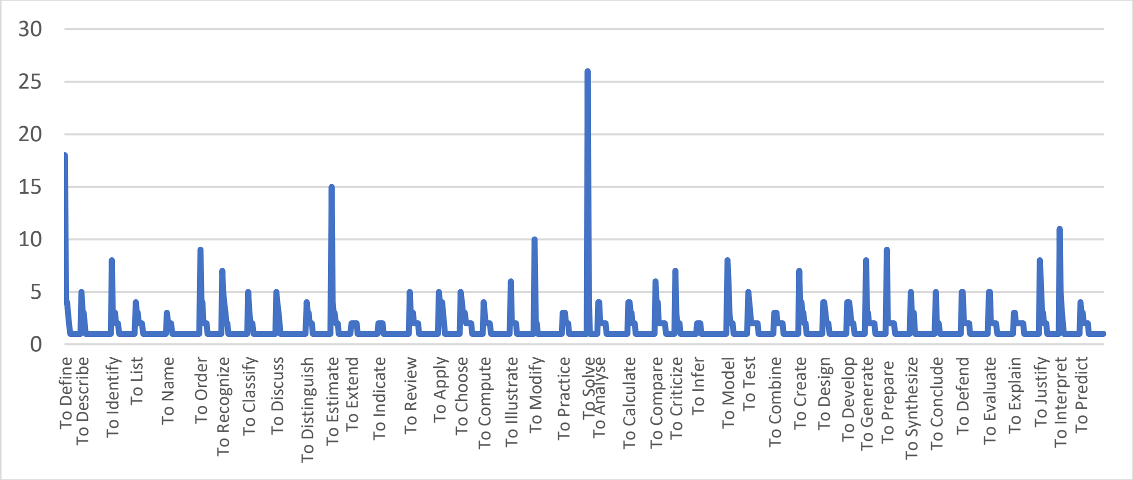

Figure 23 Frequencies of design activities

3.4. Conclusion and discussion

The goal of the empirical study was to propose a common transdisciplinary engineering design process for developing first year undergraduate engineering curriculum. The study presented the development of a complete descriptive “Transdisciplinary Engineering Design Education Ontology (TEDEO)”, which provides measures to link the design concepts across disciplines through semantics. It concludes that once the entities were defined explicitly in a frame of a certain conceptual world, no difficulty was seen in linking the concepts across disciplines; they were relatable. The TEDEO validates the hypothesis that at a higher, *abstract* level, engineering design processes share commonalities across disciplines, irrespective of the nature of the product.

NLP analysis identifies a similar understanding between design experts by using "hypernyms" as a measurement of similarity. NLP techniques in combination with WordNet, created a hypernym tree of design concepts, which connects similar meaning nouns to each other.

First, it determines what type of concepts primarily drive the design process. A greater ratio of abstract nouns compared to the physical suggests that design experts tend to think more of the abstract concepts rather than physical. This is important because the *conceptual knowledge* of design is necessary to be taught to students so that they can apply it in their professional career.

Second, it was used to count the distribution of nouns across the Bloom's cognitive domain, by tracing the verbs attached to each one of them. This activity helped in finding:

1) How the nature of design concepts shifts between physical and abstract while going through the six cognitive levels.

2) The distribution of design activities across cognitive domains.

3) The cognitive distribution of design concepts for each design stage.

The results show that the design experts suggested more nouns that are abstract in nature and belong to the lower cognitive domain of Bloom's Taxonomy, especially, the knowledge domain. The physical nouns show greater number in synthesis domain. Same holds true for the design activities which mostly belong to the first three levels of cognitive domains i.e., knowledge, comprehension and application.

It was also seen that each design stage includes all cognitive levels of thinking but they vary in each design stage, for example, knowledge domain dominates in planning stage while application domain dominates in detail design stage.

Given the similarities of design concepts and the results presented here, this study builds a strong ground for disciplines to follow a common engineering design process. The significance of Bloom's Taxonomy cannot be denied while designing the course curriculum and therefore these results can be used in the field of engineering education to enhance the design courses taught to the students at undergraduate and graduate levels.

Chapter 4. Transdisciplinary engineering design process: tracing design similarities through comparison of design stages across engineering disciplines

This chapter contributes to the second hypothesis and third action item towards achieving the overall objective. This chapter analyses the data for engineering design processes and their stages, for each discipline, from two sections of the interview, which are the open-ended questions section and the cognitive game task. The design stages obtained from both the sections were compared to the six stages of a common engineering design process. These six stages are planning; concept development; system-level design; detail design; implementation and testing; and final production. The data was compared based on the contextual meaning, design activities and definition of each design stage. Despite differing terminologies and the nature of the product, the design processes were analyzed to identify the existence of common concepts across multiple disciplines.

4.1. Introduction

The integration of technology into contemporary product development practices has transformed the engineering design process from disciplinary to transdisciplinary. This integration requires disciplines to share technologies and knowledge beyond their traditional boundaries to create an artefact. It means that the experts from various disciplines collaborate with each other to transform an initial idea into final product thus resulting in a transdisciplinary design process. (Atila Ertas, 2018) defines a transdisciplinary design process as a problem-solving activity that brings together, scientific knowledge and problem-solving techniques from multiple disciplines to solve a complex problem. (Kilian Gericke & Blessing, 2013; A. Qureshi et al., 2013; A. J. Qureshi et al., 2014) have done a significant number of industrial studies to trace the design process commonalities between engineering disciplines across a broad spectrum of industries. These studies identified a six-stage transdisciplinary design process, which is widely accepted and applicable across engineering disciplines. These six stages are *planning, concept development, system-level design, detail design, implementation & testing* and *final production.* In light of current transdisciplinary design practices in the industry (A. Ertas et al., 2003) identifies challenges currently faced by engineering education and suggests to respond to these changes by introducing transdisciplinary engineering design education.

In light of the above context, this paper is part of a current research project entitled "Transdisciplinary Design Education for Engineering Undergraduates" in the Faculty of Engineering at the University of Alberta, which is focused on the transdisciplinary engineering design processes. This research project is an empirical study that aims to highlight the similarities between the engineering design processes across multiple engineering disciplines and propose the six-stage design process as a common transdisciplinary engineering design process to enhance the undergraduate engineering education (Sharunova et al., 2017). The empirical study consisted of 34 semi-formal individual interviews with engineering design professors and academic leadership representatives in the Faculty of 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 and comparison of data obtained from participants in the second and third sections of the interviews. It is divided into various sections. Section 4.2 covers the literature review on engineering design processes. Section 4.3 describes our research methods and includes details about the interviews and the participants. The observations from cognitive game task are described in section 4.6 followed by analysis and comparison of the engineering design processes in section 4.6. The results are concluded in section 4.8.

4.2. Literature review on engineering design process

An engineering design process is a step-wise iterative approach to create an artifact (Kilian Gericke, 2011). This step-wise approach is often represented using a design process model. According to (Blessing, 1996; Eckert & Clarkson, n.d.; Kilian Gericke, 2011), a design process model consists of common structural components, also called "patterns of design", which are comprised of *design stages, design activities* and *execution strategies*.

A *design stage* is defined as a period of time after which a product changes its state (Blessing, 1996). A design process is divided into a number of design stages and 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 fulfill 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. The strategies are highly influenced by the context of the product development process.

Despite the structural similarities, design processes remain largely mono-disciplinary due to the functional and contextual differences in the product (Kilian Gericke, 2011; Kilian Gericke, Meißner, & Paetzold, 2013). shows a reflection of typical design stages from various disciplines as they are presented in the cited literature. 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.

Author	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**Stage7**
Ulrich and Eppinger	Planning	Concept development	System-level design	Detail design	Testing and refinement	Production	
RC Johnson	Problem recognition and definition	Information search	Mechanical design Synthesis	Manufacturing specifications and model configuration	Design analysis and evaluation	Production, distribution, consumption recovery cycle	
Pahl and Beitz	Planning and task clarification	Conceptual design	Embodiment design	Detailed design			
Howard et al.	Establishing a need	Analysis of task	Conceptual design	Embodiment design	Detailed design	Implementation	
Cl. Dym	Problem definition	Conceptual design	Preliminary design	detailed design	Design Communication		
Atila Ertas	Recognition of needs and requirements	Conceptual design	Feasibility study and concept reconsideration	Preliminary design	Final design	Production and testing	
C Rohrbach	Specification	Function structure	Principle solution	Module structure	Preliminary layout	Definitive layout	Product documents
Peter H. Sydenham	Establish the need	Specification	Initial design	Detail design	Modeling and testing	Production	documentation
Krutchen	Inception	Elaboration	Construction	transition			

Table 5 Common engineering design stages (Cross, 2008; Dym, Little, & Orwin, 1998; Atila Ertas, 2010; G. Pahl andW. Beitz J. Feldhusen and K.-H. Grote, n.d.; Haik, Sivaloganathan, & Shahin, 2018; Howard et al., 2008; Kruchten, 2004; Sydenham, 2004; K. T. Ulrich & Eppinger, 2011)

However, some industrial studies have demonstrated that disciplinary experts demonstrate similar understandings of the engineering design process. A study performed by Gericke and Blessing (K. Gericke & Blessing, 2012) 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. (Kilian Gericke & Blessing, 2013) conducted interviews with 23 industrial professionals and measured the applicability of similar design stages. Qureshi et al. (A. Qureshi et al., 2013; A. J. Qureshi et al., 2014) also conducted similar empirical studies with industry professionals from multiple disciplines and found a common understanding of the design stages among the discipline experts.

4.3. Research method

In light of the above literature, as well as a series of findings under the current research project (Butt et al., 2018; Sharunova et al., 2017, 2018), it was suggested to implement a similar concept of transdisciplinarity in engineering education. To conduct this study and to find a generic engineering design process as a reference, a number of design processes were studied. Based on the existing literature and current teaching practices at the University, the six-stage engineering design process described by (K. T. Ulrich & Eppinger, 2011) was chosen as a reference. The six-stages of design process *are planning, concept development, system-level design, detailed design, implementation & testing*, and *production.*

4.3.1. Research hypothesis

The research for this project was carried out with design experts from eight engineering disciplines in the Faculty of Engineering, 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 interviews were designed to understand the discipline-specific engineering design processes and their stages, and from this, assess whether or not the six-stage generic design process could truly be considered to characterize the design processes across disciplines. This common engineering design process then served as a basis to measure the similarities between design stages across disciplines. The section below describes the details of the interviews and the data obtained from them.

4.4. Participants

One-on-one semi-formal interviews were conducted with 34 engineering design professors from the Faculty of Engineering, University of Alberta. The interviews were one (1) hour long and carried out in person. The 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, from 2014 to 2017 (CEAB2017). 46 courses were identified as core design courses. Out of these 46, 23 courses, taught by 34 professors were selected for this study. The professors belong to 4 engineering departments, consisting of 8 engineering disciplines. As shown in Table 6, 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.

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

Table 6 Participant's distribution across engineering disciplines

4.5. Interview procedure

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 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 details are given below:

4.5.1. 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 and assemblies. The participants were asked whether or not 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? 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 overlap or 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.

4.5.2. The cognitive game task

The cognitive game task, based on Bloom's Taxonomy (David R. Krathwohl, 2010) combined with the proposed six-stage engineering design process (K. T. Ulrich & Eppinger, 2011) 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 planning, concept development, system-level design, detail design, implementation & testing, and final production. The 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.

4.6. Observations

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

4.6.1. Pre-game design stages

The design stages obtained from participants as a result of questions in section 4.5.1, were named as pre-game design stages, and the processes were called pre-game design processes. Table 7 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 7 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.

Department Name	Participants who follow Standard* design methods	Participants who follow formal** design method	Participants who follow informal design method but follow design stages***	Participants who do not follow any design stages	Is the process iterative	
					yes	No
Mechanical Engineering	4	4	0	2	8	0
Chemical Engineering	2	3	3	0	7	1
Civil Engineering	0	4	1	1	5	0
Electrical engineering	1	3	2	0	6	0
Total Participants	30				26	1

*Standard method: A renowned formal design method whose step by step design stage is recognized and accepted

**formal method: Where participants follow a step-by-step design process, but they do not strictly fall under any of the standard methods.

***design stages: 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.

Note: 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.

Table 7 Division of participants based on their design methods

Each participant described their systematic design process in different number of design stages. The number of stages described were independent of the discipline. Figure 24 shows the number of design stages for all participants. The average number of design stages was 5 and the maximum was 12.

The design stages as described by participants are given in Table 8. These stages were compared with the proposed six-stage design process (K. T. Ulrich & Eppinger, 2011) and it was analyzed that the core concepts behind the participants' stages are similar to the proposed stages.

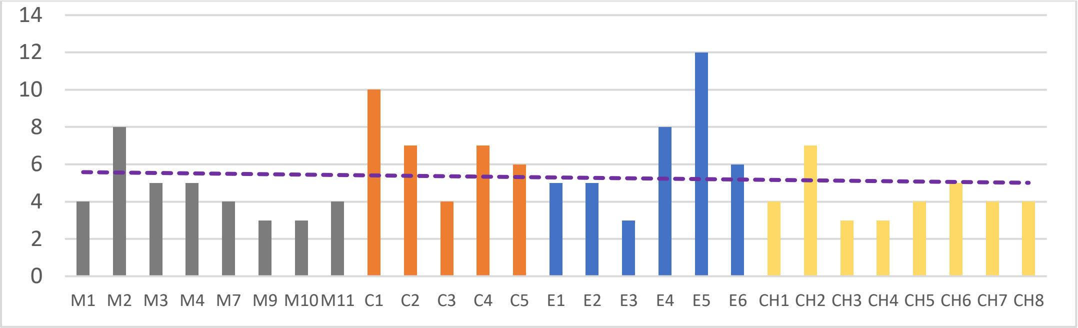

Figure 24 Number of design stages for each participant

However, the education-bound environment restricted the participants' description of design processes e.g., the proposed planning stage (K. T. Ulrich & Eppinger, 2011) is summarized as an opportunity identification phase that finishes off at definite business goals, constraints, market objectives etc., but participants' description did not include business goals or exploring the market opportunities. Given this limitation, they described the project initial stage as the constraints identification, problem definition, identification of need or other similar stages.

In addition, because there was no limitation on the number of design stages, they broke one stage into multiple design stages. e.g., concept development stage as described in literature consists of exploring alternatives and ideas, identifying needs, generating specifications, decision matrices etc. Many participants described each of this activity as a stage, thus increasing their total number of design stages. Similar case was seen for detail design and implementation & testing stage.

It was also observed that some participants did not describe production as part of their process and they argued that there was no physical prototype or production operation in their design course. They rather finished their design process at either detail design or testing stage.

Given the limitations and resulting observations, analysis of table reveals that some conceptual similarities can be seen between proposed and pre-game design stages. Majority of the participants covered the identification of need/planning, preliminary/conceptual design, detail design, implementation and testing stage.

Sr . No.	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	Stage 11	Stage 12
1	problem definition	solution specifications	conceptual design	detailed design								
2	define problem	specifications	requirements	brainstorming and literature review	concept selection and decision matrix	detailed design and calculations	prototyping	iteration				
3	establish a need	design constraints	loading systems	load calculation	site investigation and soil characteristics	estimate loading on structure	calculations to design retaining structures	cost estimation	schedule	determine factor of safety		
4	population/culture/style review	problem definition	find an approach	review Canadian (local) codes and standards	data analysis	solution	report (chapter) production					
5	project planning; criteria specifications and creative synthesis	concept development and evaluation	selection of final concept	testing and analysis	prototyping							
6	establish objective	specifications	developing 3d design and choosing one	design refinement	testing and cost analysis							
7	material characterization	volume calculation	stress and strength calculation	seepage calculation	structure evaluation for physical integrity of deposits	water balances evaluation	effects and errors and failure modes evaluation					
8	problem definition (client's needs)	generate ideas and brainstorming	design options	evaluation (matrix spec table)	detailed design (choice	costs	generate 1-2 designs	choose one & finalize	physical prototype	analysis	report	building (prototype)
9	know relevant code and regulations	limits and boundaries	practical aspects	conceptual design	specifics of the design	present the project						
10	exploratory	development	evaluation									

11	defining problem	find bottleneck	knowledge to troubleshooting										
12	objective definition	generate possible solutions	select single solutions	evaluate solution and analysis	estimated output and comparison with ideal objective								
13	problem definition	problem analysis	idea diagrams	design	detailed design	testing	implementation	coding iterations					
14	problem definition and check constraints; specs	preliminary design	technical (detailed calculations) design	final report (testing and production)									
15	problem definition and choice of tools	material processing and background	macro analysis	material testing									
16	objective	explore	appraise	select	define	execute	operate						
17	discover	define	develop	deliver									
18	conceptual report (problem definition; management and brainstorming; specs; planning)	analysis report (technical analysis of components and sub-system)	final report (iteration and improvement)										
19	customer requirement collection	concept design	detailed design; prototyping; production										
20	task clarification	conceptual design	embodiment design	detailed design									
21	find client need	working to find appropriate software	prototype	feedback	refinement	extension							

22	tool identification	structure selection	parameter selection									
23	problem definition	finding relevant variables	get reasonable number for each variable	try with number if it works	verify and optimize							
24	analyze problem	understand data	generate solution	evaluate solution								
25	assess the system	select or identify material and its strength	stepwise detailed calculations	work with 1 solution								
26	problem formulation	data collection	equations and stress level	comparing with actual conditions	re-select materials							
27	objective definition	generate possible solutions	select single solutions	evaluate solution and analysis	estimated output and comparison with ideal objective							

Table 8 Participants’ pre-game design stages

4.6.2. Post-game design stages

The design stages named by the participants during the cognitive game task were referred as post-game design stages. The game was conducted with all of the 34 participants and the observations are shown in Table 9. The “√” and “x” values were assigned against each stage of the design process for all participants. The “√” value appears if participants agreed to the proposed design stage. The “x” value appears if they chose to rename the design stage.

Department	**Planning**	**Concept Development**	**System-level design**	**Detail design**	**Implementation & Testing**	**Final Production**
Mechanical	×	×	×	×	√	√
	×	×	×	×	×	×
	×	×	×	×	×	×
	×	×	×	×	×	×
	×	√	√	×	×	√
	√	√	√	√	√	√
	√	√	√	√	√	√
	×	√	√	√	√	√
	√	√	√	√	√	√
	×	√	×	√	×	×
	×	√	√	√	√	×
	×	√	√	√	×	√
	√	√	√	√	√	√
Civil	×	×	×	×	×	×
	×	×	×	×	×	×
	×	×	×	√	×	×
	√	√	×	√	√	×
	×	×	√	√	√	√
	×	√	√	√	√	×
Electrical	√	√	√	√	√	√
	×	×	×	×	×	×
	×	×	×	√	×	×
	×	√	√	√	×	√
	×	√	×	×	×	√
	√	√	√	√	√	√
	×	×	×	×	×	×
Chemical	√	√	√	√	√	√
	×	×	√	√	×	×
	√	√	√	√	√	√
	×	√	√	√	√	√
	√	√	√	√	√	√
	√	√	√	√	√	√
	√	√	√	√	√	√
	×	×	×	×	×	×

Table 9 Details of the participants who agreed/not agreed to the proposed design stages

As it can be seen, 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 25 and Figure 26 show the percentage and frequency count of all participants who agreed to the proposed design stages. Figure 27 shows the similar percentage for individual departments. As can be seen, *planning, implementation & testing* for individual participants are as low as 35% and 50% respectively. Many of the participants claimed that instead of planning stage and testing stage in their curriculum, they have other similar stages such as problem definition, objective, problem analysis etc. Similarly, there was no *final production* stage for many participants from civil department. They argued that instead of a physical prototype their final product was an evaluation report. In Figure 27, an agreement percentage of 17% from civil shows that a higher percentage of participants renamed planning stage.

On average, many of the participants from civil and electrical chose to rename most of the design stages thus shown by lower percentages by individual departments in Figure 27. 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. The complete names of all the design stages mapped by participants are given in Appendix A.4. Design stages comparison.

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. As shown in Figure 27, the agreement is maximum from chemical followed by mechanical discipline, which means the proposed stages were the same as taught by these disciplines. A discussion on the comparison of pre- and post-game design stages is given in the next section.

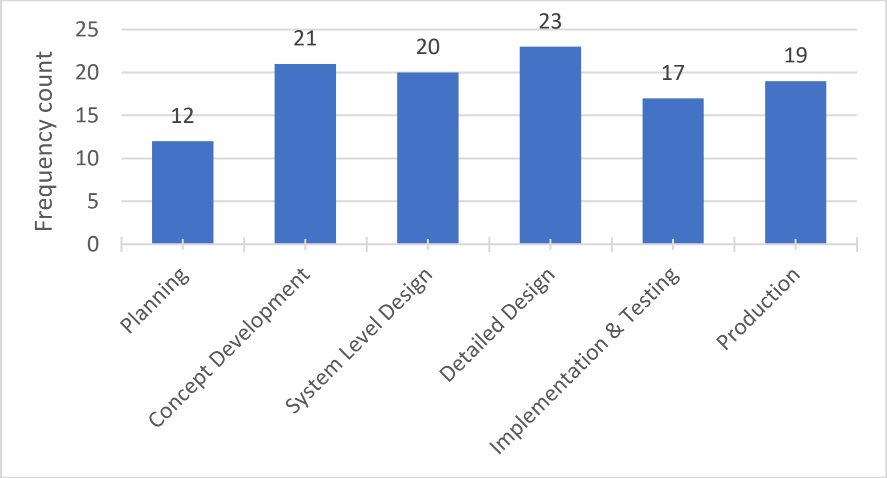

Figure 25 Frequency of individual participants who agreed to the proposed design stages

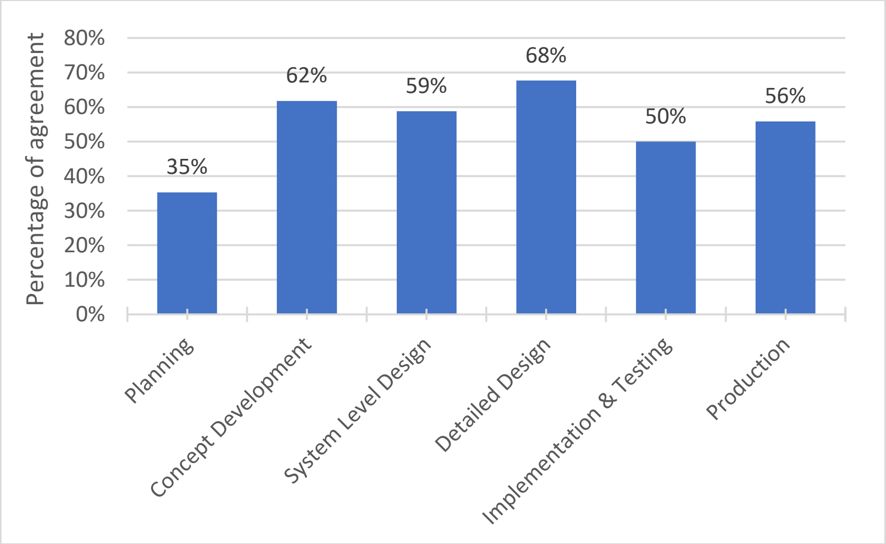

Figure 26 Percentage of individual participants who agreed to the proposed design stages

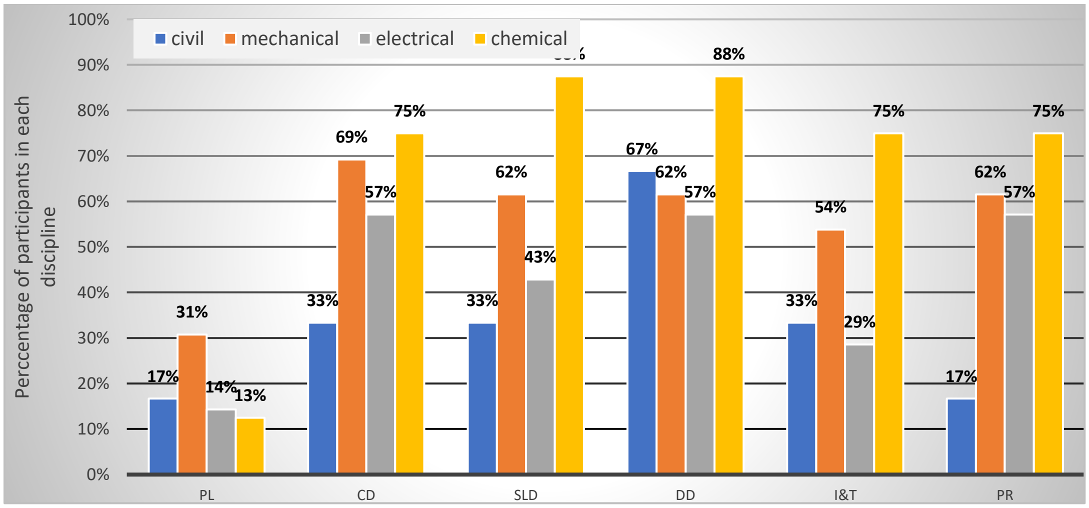

Figure 27 Individual disciplines who agreed to the proposed design stages

4.7. Discussion

A comparison of pre- and post-game design stages revealed the following:

1. All participants, except 1, agreed that the design process is iterative. The iteration occurs within as well as across the design stages.
2. 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 need or synonymously similar design stage. These design stages are considered similar to the planning stage of the proposed process because they are described as activities of the planning stage in that process. Approximately 29% of participants finished their pre-game design process with production/prototyping/execution stage. Participants who finished their design stages at a stage other than production claimed that they did not teach course in which the production or prototype was required. They did, however, agreed that generally the production/execution is the final stage of the design process.

3. None of the participants reordered the proposed six-stage common engineering design process.
4. 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, majority of them had no difficulty in mapping or renaming the proposed stages to better suit their meaning. Despite the difference in the names, the mapping did not change the conceptual meaning of our proposed design process.

4.8. Conclusion

This paper presented an empirical study on transdisciplinary engineering design processes between multiple disciplines. The results from 34 interviews with engineering design professors regarding their design processes and stages were discussed. Results were based on the analysis of the two parts of the interviews: 1) the open-ended questions regarding the design process methodologies and design stages used by engineering professors for teaching design in their respective disciplines; and 2) a cognitive game task, where participants re-named the stages of the suggested common six-stage engineering design process based on their disciplines.

A comparison 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. Despite different names given to those stages, they understand the design process at an abstract level. This 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. However, when participants were given the proposed six-stage design process, 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 on mapping of design stages, the study shows that, at a conceptual level, the common design process is independent of the disciplinary boundaries. It means the conceptual similarities 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 study 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.

Chapter 5. Application of research

This chapter explains the use of semantic similarity measures in analyzing the design content of engineering design books taught across the faculty of engineering at the University of Alberta. The objective of this analysis was to:

1) Observe the cognitive patterns of design concepts in each book.

2) Analyze the semantic relatedness of design concepts within as well as between different design books. The results are presented as visual graphs in the form of clusters and networks.

5.1. Introduction

After analyzing the results of the interviews, it was decided to implement the same methodology, of using Bloom's Taxonomy combined with NLP techniques, to observe the distribution of design concepts in the course books. This activity was performed to:

1) Support the investigation of identifying semantic links between the design elements taught in each discipline.

2) Investigate the dominance of cognitive levels based on the complexity of design concepts taught

3) Validate the occurrence of design activities in textbooks.

To conduct this part, the first step was contacting the interviewed participants to recommend some engineering books, which they consider relevant to their disciplinary design concepts. The following number of books were received from all disciplines as shown in Table 10.

Discipline	**Quantity**
Mechanical	8
Petroleum	5
Chemical	4
Electrical	5
Civil	5
Materials	12

Table 10 Recommended books from each discipline

Based on responses received, the following books were shortlisted.

1. Chemical Engineering Process Design and Economics: A Practical Guide (G. D. Ulrich & Vasudevan, 2004).
2. Highway Geometric Design Guide (1995) by Alberta Transportation. [Updated to 1999] (http://www.transportation.alberta.ca/951.htm).
3. Power Electronics: Converters, Applications, and Design, by Ned Mohan , et al. Third Edition. (Mohan & Undeland, 2007).
4. Eppinger, Steven D., and Karl T. Ulrich. "Product design and development." (1995) (K. T. Ulrich & Eppinger, 2011).
5. Dieter, George, and L. C. Schmidt. Engineering design, engineering series. New York, NY: McGraw-Hill, 2008 (Dieter & Schmidt, 2008).

However, before analyzing these books, a test analysis was performed on two of the highly cited books in the field of engineering literature namely: Engineering design: A systematic approach (G. Pahl andW. Beitz J. Feldhusen and K.-H. Grote, n.d.) and product design and development (K. T. Ulrich & Eppinger, 2011). This activity is called an “application test”, whose methodology is explained below.

5.2. Methodology of creating similarity network

This methodology describes a step-by-step procedure for calculating the co-occurrence of nouns with Bloom's cognitive verbs. The co-occurrence matrix is also used for finding noun-to-noun and verb-to-verb similarities. Before describing the methodology, definitions of a few terms are given below, which are taken from (Daniel, James, & Martin, 2016).

1. *Word to word co-occurrence matrix*: a matrix in which each cell counts the number of times a word is used with another word, in some context.
2. *Tokenization*: separating each word in a sentence based on the white spaces between them e.g., the phrase *design has many forms* has four tokens in it.

The text below describes the steps taken to create the graphs of nouns as well as verbs. A systematic layout is shown in Figure 28.

1. **** The books were converted from PDF to TXT format using Adobe acrobat DC (https://acrobat.adobe.com/ca/en/acrobat.html).
2. Python was used to separate each word of the extracted text through tokenization (Webster & Kit, 1992) in the form of a list using (RegexpTokenizer) from NLTK (https://www.nltk.org/).
3. The list of tokenized words was used as an entry for the Stanford POS tagger (https://nlp.stanford.edu/software/tagger.shtml), which tagged each word into different categories of nouns, verbs, propositions, objectives etc. A description of each category is given in (Daniel et al., 2016). The output of POS tagger is a list of words tagged as noun, verb, adjective, proposition etc.

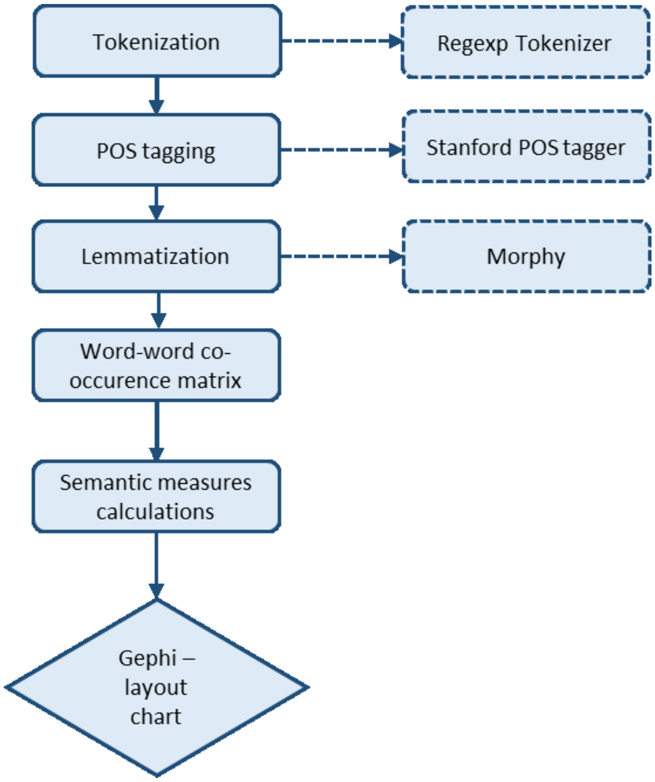

Figure 28 Layout for semantic similarity calculation

4. Next, a word-to-word co-occurrence matrix was created. Following steps were taken to generate this matrix.

  i. The 42 verbs from Bloom's Taxonomy were used to determine the context of the matrix. So, each one of these verbs in the text had a word window created around it. The size of this window was 15 with the verb in the middle.

  ii. Within this window, all other words were deleted except a) the verb from Bloom's Taxonomy, and b) the words tagged as nouns.

  iii. With only one verb and some nouns inside the window, it is time to build a noun-to-verb co-occurrence matrix. First, each word is converted to its infinitive form by the WordNetLemmatizer tool, (morphy) inside NLTK library. NLTK has an interface to WordNet; therefore, it has functions that can access and use WordNet lexical database and algorithms. NLTK’s interface was used to access WordNet to use its lemmatization tool. The part of the code that created co-occurrence matrix is given below.

```
print('create_coocmatrix started')

        lemmatizer = nltk.stem.WordNetLemmatizer()

        window_verbs = []
        window_nouns = []

        progress = 0
        for window in windows:  # Iterates over the windows
            progress += 1
            central_verb_index = window[1]
            window = window[0]

            word_counter = 0
            for (word, tag) in window:  # Iterates over each tagged word inside the window

                if word_counter == central_verb_index and tag.startswith('V'):  # If it is a verb store it on a
    dictionary and increase the size of
                    # columns
                    if enable_lemmatization:
                        word = lemmatizer.lemmatize(word, 'v')

                    word = 'to ' + word
                    window_verbs.append(word)
                    if word not in self.verb_columns:
                        self.verb_columns[word] = self.verb_columns_size
                        self.verb_columns_size += 1
                        if self.verb_columns_size > 2:
                            self.matrix = np.lib.pad(self.matrix, ((0, 0), (0, 1)), 'constant', constant_values=0)

                if tag.startswith('NN'):  # If it is a Noun do the same as the verbs, but increase the rows

                    if enable_lemmatization:
                        word = lemmatizer.lemmatize(word)

                    if word not in self.noun_freq:
                        self.noun_freq[word] = 1
                    else:
                        self.noun_freq[word] += 1

                    window_nouns.append(word)
                    if word not in self.noun_rows:
                        self.noun_rows[word] = self.noun_rows_size
                        self.noun_rows_size += 1
                        if self.noun_rows_size > 2:
                            self.matrix = np.lib.pad(self.matrix, ((0, 1), (0, 0)), 'constant', constant_values=0)

                word_counter += 1

            for verb in window_verbs:  # fills the matrix with the co-occurrences
                j = self.verb_columns.get(verb)
```

```
        for noun in window_nouns:
            i = self.noun_rows.get(noun)
            self.matrix[i][j] += 1

    window_verbs.clear()  # Clear temp lists for next iteration
    window_nouns.clear()

print('create_coocmatrix ended')
```

5. With that done, the noun-to-verb co-occurrence matrix was created in which the rows are representing the nouns and the columns are representing the verbs from Bloom’s Taxonomy. The maximum number of columns was 42 which is equals to the number of verbs from Bloom’s Taxonomy. Each cell of the matrix contained the number of times that the noun of a row co-occurred with the verb in a column. With the co-occurrence matrix ready, a set of arrays is created. Each of them stored the nouns that most co-occurred with one of the 42 verbs. A total number of 726 unique nouns were found in the book. Each pair of noun and verb make an activity as shown in Figure 29. It shows each verb with node sizes varying according to the number of nouns attached to each of these verbs. For example, “To create” has a maximum number of 94 nouns connected to it and therefore has the biggest node size compared to “To identify” with 78 nouns attached to it. Similarly, the thickness of each edge shows the number of times a noun comes with a verb to form an activity. For example. “product” occurred 133 times with “To develop”, which is the highest occurring activity in the network, thus giving it a thicker edge than “concept” that repeated 51 times with “To generate”. In addition, the minimum frequency of a design activity considered for developing the network is 3, which means that all the noun-verb pair are occurring 3 or more times together as an activity.

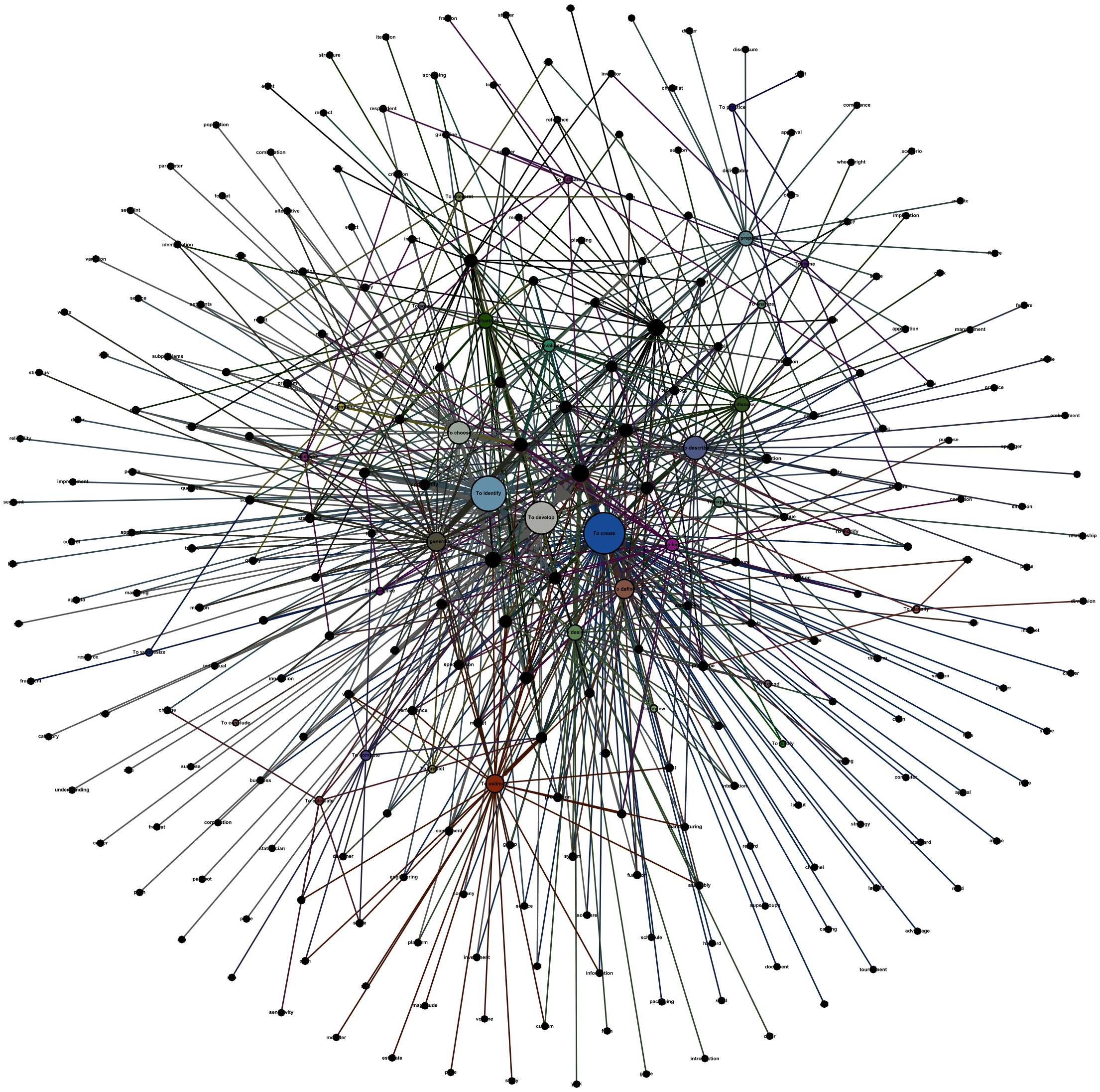

Figure 29 Complete design activities

For illustrative purpose, Figure 30 shows all the design activities with frequencies equals to or greater than 10. As discussed before, product design and development process utilizes all cognitive domains at different levels, which, can be seen in the figure. The verbs from all cognitive levels pair up with nouns to form design activities. Below is an analysis of the network followed by a concise discussion.

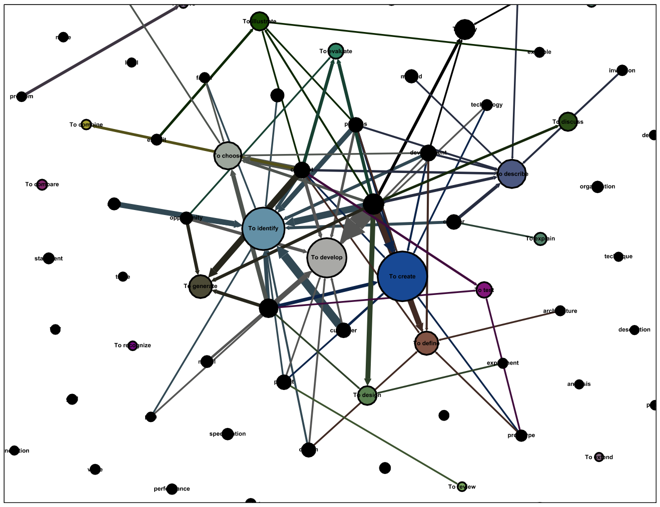

Figure 30 Design activities occurring 10 or more times

Highest occurring activities: The Following list of activities was traced to see which activities are addressed the most in the book. It is interesting to note that all the highest occurring activities belong to product, customer and concept of design with knowledge and synthesis as the dominant cognitive levels.

Activity	Frequency
To develop-product	133
To identify-customer	67
To create-product	62
To identify-product	54
To generate-concept	51

Table 11 Highest design activities

Number of connecting edges: Table 12 shows the number of verbs in descending order, that paired up with any of the nouns to form a design activity. It is interesting to note, that although “To create” has a bigger node size than “To identify”, it has less number of connecting edges. It happened because; “To create” is connected to less *variety of different nouns* thus giving it less number of total connecting edges. Again, similar to the previous division, the knowledge and synthesis domains are dominating, which means the most important concepts taught to the students belong to these two domains.

Verbs	Frequencies
To identify	704
To develop	629
To create	557
To describe	305

Table 12 Frequencies of verbs based on connecting edges

Highest occurring nouns: Next, the network was analyzed to see which nouns occur the most, irrespective of their connecting verbs. Table 13 shows the frequency of nouns in descending order.

Nouns	Frequency
product	492
Concept	282
Team	187
Customer	105

Table 13 Frequency of highest occurring nouns

Highest number of unique nouns: The term unique means any noun despite coming 133 times in the network, would be counted as one unique noun. Based on unique number of nouns attached, “to create”, “to identify” and “to develop” are the highest occurring verbs making 94, 78 and 71 number of unique activities, respectively.

The activities shown above are equivalent to those collected manually from the cognitive game task, performed by the participants. Given the above observations and results, it is easy to see that the design concepts taught to students belong to all cognitive levels, in which knowledge and synthesis are the dominant. Discussion on Figure 33 confirms the same. In addition, a majority of highest occurring design concepts found in the book are abstract rather than physical, which validates the observation with participants that design concepts taught to the students are abstract rather than physical, however, the only two highest occurring concepts; product and customer are physical in nature.

In addition to few nouns given in the list, a close view to Figure 30 shows that the nouns making up design activities are the same as reported by participants and analyzed by the researcher as the highest occurring nouns. Those nouns are given in Appendix A.2. Some examples include product, concept, opportunity, customer, process, cost etc.

6. At the same time, nouns collected by the algorithm are used to create a noun-to-noun matrix. This matrix is created in the same way as the noun-to-verb co-occurrence matrix, the only difference is that the number of columns are now equal to the number of nouns, that is, both rows and columns contained the nouns. Each cell of the matrix represents the semantic similarity between two nouns ranging from 0 to 1; 1 being the highest. The semantic relatedness is computed using WordNet by getting the first synset[2]/set of synonyms returned by searching for the noun. After the synsets for the row nouns and for the column nouns were obtained, the semantic similarity between each two nouns is computed by the similarity measures described in section 3.2.3. The similarity measures calculate the edge weight between each pair of nouns, which is defined as a measure of "connection strength" between any two nodes. Higher similarity means a strong connection and is therefore, represented by a thicker edge. The original graph contains many connections where each noun is connected to every other noun with a varying value

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[2] WordNet groups English words into sets of synonyms called "synsets" that provide short definitions of each word and describe their usage (https://en.wikipedia.org/wiki/WordNet).

of edge weight. Figure 31 shows the results with edge weight greater than and equals to 0.5. The graph shows clusters of nouns based on their categories according to section 2.3.4. Starting from the top, the clusters of objects and process are in the middle while proposition and attributes are at the top and bottom edge, respectively while the relation is at the bottom middle of the figure. The big and small circles represent the number of nouns linked to each node. The more a noun is linked to other nouns, the bigger it becomes. “Idea”, for example, is semantically similar to more number of nouns as compared to “concept” and “knowledge”.

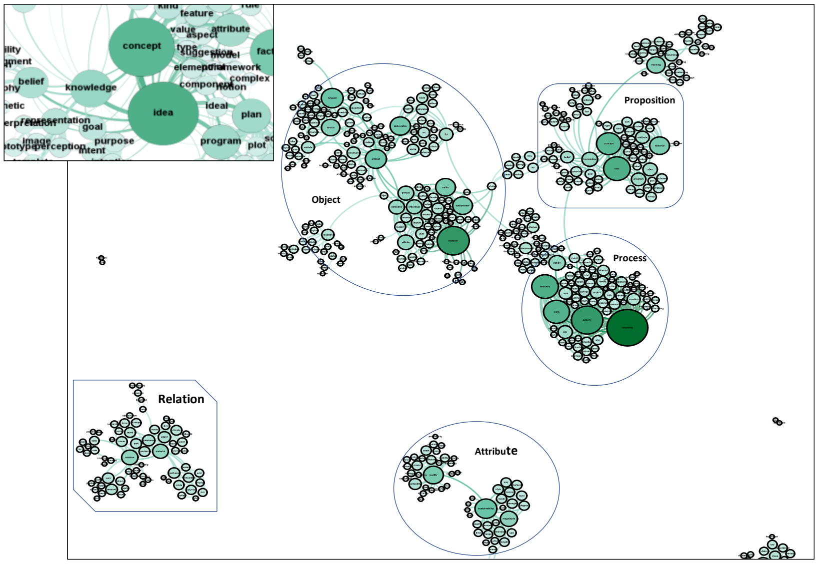

Figure 31 Representation of semantic similarity between nouns

7. Next, a data file is created using the format ‘.gdf’ which is loaded into Gephi (Bastian, Heymann, & Jacomy, 2009), an open-source visualization tool (https://gephi.org). Force Atlas 2 layout was chosen to visualize the results. The same method was repeated to analyze the similarity between books. The nouns from each book were given a special colour. Brown nodes represent nouns from (G. Pahl andW. Beitz J. Feldhusen and K.-H. Grote, n.d.), golden nodes represent (K. T.

Ulrich & Eppinger, 2011), while black nodes are those which are lexically same in both the books. The results in Figure 32 were produced as clusters based on the physical (2 clusters on the bottom right) and abstract nature of nouns addressed in each of the books. Here each node is connected to another node; however, the similarity is represented in terms of edge thickness and the distance between each pair of nodes. Higher edge thickness and less distance mean a greater similarity. For example, the inset is showing the semantic relatedness between design concepts at an edge weight of 0.7. In the view, the highlighted portion from cluster of abstract nodes is showing "thought" is more similar to "concept" in meaning than "kind". In addition, the size of nodes is showing that "sort" is connected to a less number of nouns than the "concept", thereof concluding that "concept" is more generalized and subsumes a large number of words than "sort".

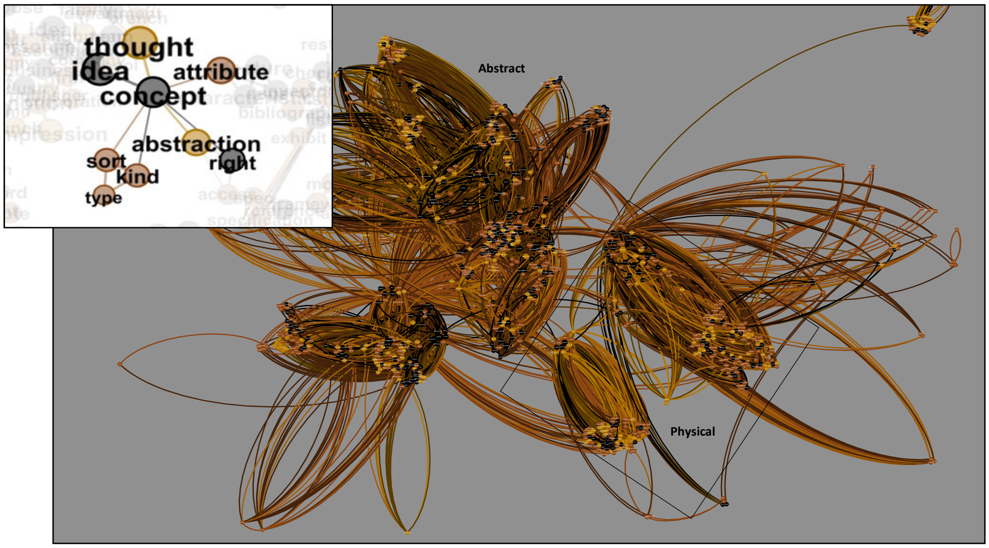

Figure 32 Semantic similarity between engineering design books

8. In order to find the cognitive distribution of action verbs in books, a general list of Bloom's action verbs was compiled (Sharunova et al., n.d.) to create a verb-to-verb

co-occurrence matrix. The matrix was created the same way as described before, with columns filled with compiled verbs list, and rows filled with the verbs found in the book. Each cell of the matrix represents the semantic similarity between two verbs ranging from 0 to 1; 1 being the highest. Figure 33 shows Bloom's Taxonomy domains with node sizes varying according to the number of similar meaning verbs attached to them. The inset on the left is showing a bigger view of verbs around synthesis domain. The figure identifies that most of the nouns in the book relate to higher cognitive thinking, i.e., synthesis. Synthesis refers to the creation of things which is categorized into producing and generating (Krathwohl, 2010), followed by knowledge domain which refers to learning basic knowledge of a thing. The dominance of these two domains means a large part of the book teaches concepts about defining, identifying, assembling, creating things, etc.; which means that students learn the basic knowledge as well as the principles and concepts of the creation of a product. However, it does not mean the other part of cognitive levels are neglected; it does address other levels but at a smaller extent as shown in the figure.

5.3. Conclusion

The scope of this chapter was to validate the same NLP methods, applied during the thesis, to justify the scope of methodology. It was done in three stages. First, NLP was used to find the verb-noun pairs/design activities from the engineering design books, similar of the kind as obtained through cognitive game task performed by participants. Next, an average of four similarity measures (Jiang & Conrath, 1997; Leacock & Chodorow, 1998; Lin, 1998; Wu & Palmer, 1994) were used to calculate semantic relatedness between each pair of nouns in the book. The activity was repeated to calculate the similarity between (K. T. Ulrich & Eppinger, 2011) and (G. Pahl andW. Beitz J. Feldhusen and K.-H. Grote, n.d.).

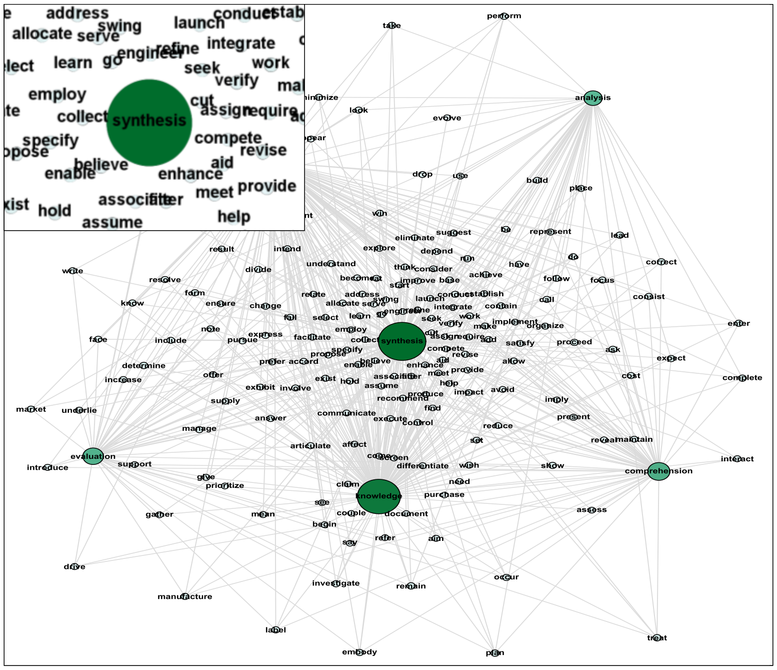

Figure 33 Highest occurring verbs from the general list of Bloom’s Taxonomy

These activities generated similar kinds of semantic links, as obtained manually from SUMO, which connected one noun to another similar meaning noun. The results were in the form of clusters, divided into physical or abstract concepts.

In addition, the distribution of action verbs against a general list of Bloom’s verbs identified that the concepts taught in the book were distributed across all cognitive levels, with synthesis and knowledge being the highest. This analysis can be used to conclude that in addition to basic knowledge, students are also taught the basic principles of combining the knowledge to *create* products.

As expected, the design components in the books were classified as either physical or abstract. After a certain edge weight, they were visibly divided into categories of objects, process, attributes, proposition etc. It was also noticed that the clusters contained more components of abstract nature, which means they relate to the conceptual principles and information behind the design of a component. This is very important because it incorporates a huge portion of knowledge, understanding and application of design. However, it is interesting to know that the clusters contain a small portion of physical entities, which means these books contain less information about visualization or actual prototyping/production phases of a product.

The above two observations conclude that the design concepts taught in the design books are abstract in nature with a greater emphasis on synthesizing the conceptual knowledge i.e., knowledge of basic terminologies, components, design theories and their working principles. In light of the results achieved, the research may be carry forward by applying the same methodology in the analysis of design books from all other disciplines.

Chapter 6. Conclusion

6.1. General conclusion & research contributions

Tracing the design commonalities across multiple engineering disciplines has proven to be a promising method in introducing a transdisciplinary engineering design process to the first-year undergraduate students' curriculum. This research provides an empirical basis to validate the mutual understanding of a six-stage engineering design process between engineering disciplines in the Faculty of Engineering at the University of Alberta. These six stages are planning, concept development, system-level design, detail design, testing & implementation and final production. This thesis is based on 34 structured interviews, designed to collect the engineering design activities, design concepts, the discipline specific engineering design processes, and their stages as taught by professors. The research validates that the proposed design process and its stages are relatable to the discipline specific design processes and their stages. Therefore, it can be proposed as a common engineering design process to be taught to the first-year students.

The thesis first identifies the fundamental barriers in achieving transdisciplinarity between engineering disciplines. These barriers are terminology differences and the discipline specific design processes, tools and methodologies taught to the students. Consequently, when students enter into a transdisciplinary industry environment they have to do a considerable effort to understand design from multiple departments' perspective.

This research provides solution to overcome these fundamental barriers across disciplines in the following ways: 1) Tracing the commonalities of design concepts 2) identifying and tracing the discipline specific design stages and comparison of these stages with the proposed six-stage engineering design process.

First, it focuses on a method of tracing the commonalities of design concepts through a cognitive game task that was used to collect the common engineering design concepts from each discipline, followed by an activity of choosing an engineering-related definition for each concept. Next, the convergence of semantically similar design concepts, based on their extrinsic meaning as defined by SUMO, gives rise to the Transdisciplinary Engineering Design Education Ontology (TEDEO). In this ontology, each concept from a discipline connects to another semantically similar concept from another discipline.

In addition to the above analytical approach, the thesis implements the computational approach to measure the semantic links between design concepts, through NLP techniques. The NLP techniques connect semantically similar words across disciplines by tracing their common hypernym and creating a hypernym tree for each design stage. In this hypernym tree, each concept from a discipline connects to another semantically similar concept from another discipline. The hypernym trees also segregate the design concepts as either Physical or Abstract. The division of design concepts into either of these classes verifies that the concepts taught to students are inclined more towards the abstract/conceptual nature of the product rather than physical. An implication of this conclusion leads us to the possible future investigation described in Section 6.2.

Second, the thesis investigates the similarity between engineering design process stages across multiple engineering disciplines. The context-based approach reveals that all discipline experts have a clear understanding of the design process and its sequential stages. Despite different names given to disciplinary design stage and the nature of product, they agree upon the proposed common six-stage engineering design process.

However, in addition to empirical studies, there is a room to improve the results of transdisciplinary design thinking by analyzing the course material taught to the students during the 3 years of their specialization.

The results of research not only have implications in the field of education, their diversity is equally effective in industrial sector. The research methodology can be adapted in industry to achieve an integration of design concepts across multiple disciplines i.e., a similarity of design concepts can be traced by following TEDEO extraction approach. The application may also be extended towards managing the company portfolio, documents database as well as the functional and hierarchical network of organization.

Similarly, the understanding of the application of Bloom's taxonomy during design is especially beneficial to apply relevant information at each stage of design process, which is important to achieve smart design product. The application of cognitive game is important to distinguish the kind of activities that occur in each discipline and thereby identify the occurrences of semantically similar design tasks and concepts. The research methodology can also be used to identify the importance of physical and abstract design concepts and their percentage occurrence at each stage of the process, which leads us towards one of the possible future research, outlined in next section.

6.2. Research contributions & future research

The contributions of this research are described below:

1) Developing a cognitive game, first of its kind, where the cognitive psychology and a six-stage engineering design process were combined to extract the most commonly occurring engineering design concepts from each discipline. Participant's understanding of engineering design process supported by Bloom's

Taxonomy played a significant role in identifying the complexities of communication barriers across engineering disciplines. The results from this activity form the basis of this research.

2) Creating a Transdisciplinary Engineering Design Education Ontology (TEDEO) by specifying the extrinsic meaning of design concepts collected through contribution 1. This is the first version that can be expanded by incorporating other information sources in the engineering faculty, e.g., lecture materials and course books (objective 1).

3) Investigating the nature of design concepts and verifying the semantic relations between them across multiple disciplines, through the application of NLP techniques. Similarity measures were used in combination with Bloom's Taxonomy to trace the common hypernyms and see the behavior of design concepts thereby creating semantic links between them (objective 2).

4) Devising a methodology for tracing and synchronizing the design stages taught in multiple engineering disciplines. It consisted of collecting the discipline specific design stages described and self-mapped by participants. This together combined with the literature review on design process, supported in identifying the commonalities of engineering design stages (Objective 3).

The following areas in this thesis require further research:

1) The detail analysis of suggested books can lead to a valuable design content, which can be included to expand our ontology. It will help in understanding the nature of concepts in more detail.
2) The results from thesis identify that design experts tend to think more of the abstract concepts while describing the activities of a design process. It would also be interesting to investigate the expert's design thinking from various industries. A potential research could be "Design thinking: a comparison of product between education and industrial design experts.

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Appendix A

A.1. Design activities table

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
To Define (Total design activities=42)	problem	18	To Describe (Total design activities=38)	process	5
	objective	4		needs	3
	specifications	4		problem	3
	scope	3		concept	2
	needs	2		features	1
	opportunity	1		opportunity	1
	options	1		options	1
	constraints	1		alternatives	1
	statement	1		constraints	1
	application	1		users	1
	solutions	1		roles	1
	system	1		requirements	1
	challenges	1		design	1
	assumptions	1		product	1
	concept	1		failure	1
	process	1		time frame	1
To Identify (Total design activities=39)	problem	8		specifications	1
	needs	3		functions	1
	solutions	3		results	1
	components	3		scope	1
	goals	2		case	1
	weakness	2		behaviors	1
	parameters	2		justification	1
	options	1		method	1
	alternatives	1		relations	1
	constraints	1		closure	1
	risks	1		meaning	1
	possibilities	1		use	1
	resources	1		operation	1
	hazards	1	To List (Total design activities=41)	requirements	4
	limitations	1		alternatives	3
	variables	1		specifications	3
	advantage	1		options	2
	physics	1		possibilities	2

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	errors	1		components	2
	scenario	1		equipment	2
	synergies	1		constraints	1
	process	1		ideas	1
	bug	1		tasks	1
To Name (Total design activities=38)	leader	3		needs	1
	alternatives	2		issues	1
	requirements	2		solutions	1
	design	2		benefits	1
	company	2		materials	1
	opportunity	1		assumptions	1
	constraints	1		problem	1
	ideas	1		structure	1
	data	1		variables	1
	project	1		pros and cons	1
	possibilities	1		physics	1
	issues	1		parameters	1
	system	1		investigation	1
	chart	1		load	1
	specifications	1		parts	1
	functions	1		path	1
	materials	1		standards	1
	problem	1		regulations	1
	variables	1		importance	1
	components	1		list	1
	topology	1	To Order (Total design activities=39)	parts	9
	approach	1		priorities	4
	equipment	1		components	4
	concept	1		solutions	2
	method	1		process	2
	classes	1		BOM	2
	suppliers	1		supplies	2
	parts	1		tasks	1
	process	1		data	1
	representative	1		design	1
	invention	1		product	1

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	engineer	1		causes	1
To Recognize (Total design activities=42)	needs	7		materials	1
	problem	5		management	1
	limitations	4		structure	1
	errors	3		discipline	1
	constraints	2		facts	1
	challenges	2		equipment	1
	alternatives	1		software	1
	ideas	1		characterization	1
	data	1		tool	1
	requirements	1	To Classify (Total design activities=36)	materials	5
	design	1		solutions	3
	potential	1		options	2
	solutions	1		alternatives	2
	failure	1		stages	2
	priorities	1		opportunity	1
	flaws	1		constraints	1
	advantage	1		ideas	1
	weakness	1		tasks	1
	trends	1		needs	1
	cost	1		requirements	1
	patterns	1		selection	1
	strength	1		models	1
	drawbacks	1		problem	1
	bug	1		variables	1
	deficiency	1		soils	1
To Discuss (Total design activities=39)	solutions	5		codes	1
	alternatives	4		components	1
	problem	3		objects	1
	ideas	2		approach	1
	opportunity	1		sub section	1
	data	1		sub-system	1
	needs	1		waste	1
	requirements	1		properties	1
	outcome	1		things	1
	potential	1		process	1

Verbs	**Nouns**	**Design activities**	**Verbs**	**Nouns**	**Design activities**
	members	1		importance	1
	product	1	To Distinguish (Total design activities=34)	alternatives	4
	definition	1		solutions	3
	challenges	1		method	3
	benefits	1		design	2
	teamwork	1		benefits	2
	decisions	1		differences	2
	rationale	1		options	1
	goals	1		ideas	1
	limitations	1		needs	1
	Analysis	1		roles	1
	results	1		failure	1
	advantage	1		decisions	1
	pros and cons	1		stages	1
	approach	1		problem	1
	aspects	1		areas	1
	commitment	1		case	1
	method	1		nice-to-have	1
	relations	1		equipment	1
To Estimate (Total design activities=43)	cost	15		load	1
	time	4		decision matrix	1
	efforts	3		mechanisms	1
	values	3		process	1
	schedule	2		optimum	1
	load	2		anomalies	1
	descriptions	2	To Extend (Total design activities=32)	ideas	2
	opportunity	1		functions	2
	constraints	1		life	2
	needs	1		scope	2
	outcome	1		approach	2
	variables	1		deadlines	2
	size	1		thoughts	1
	efficiency	1		criteria	1
	performance	1		schedule	1
	strength	1		literature	1
	Profit	1		project	1

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	weight	1		requirements	1
	financials	1		application	1
To Indicate (Total design activities=35)	solutions	2		design	1
	codes	2		solutions	1
	advantage	2		system	1
	direction	2		timelines	1
	meaning	2		reasoning	1
	options	1		collaboration	1
	possibilities	1		Analysis	1
	design	1		knowledge	1
	challenges	1		areas	1
	selection	1		concept	1
	preference	1		skills	1
	problem	1		framework	1
	priorities	1		support	1
	flaws	1	To Review (Total design activities=43)	reports	5
	differences	1		literature	3
	responsibilities	1		design	3
	feasibility	1		calculations	3
	components	1		product	2
	weakness	1		results	2
	behaviors	1		codes	2
	parameters	1		paper	2
	tonnage-grade	1		drawings	2
	mistakes	1		options	1
	errors	1		ideas	1
	relevance	1		tasks	1
	path	1		data	1
	strength	1		issues	1
	controls	1		system	1
	improvement	1		resources	1
	investors	1		specifications	1
To Apply (Total design activities=37)	knowledge	5		teamwork	1
	principles	4		test	1
	concept	4		attributes	1
	method	4		assignment	1

Verbs	**Nouns**	**Design activities**	**Verbs**	**Nouns**	**Design activities**
	fundamentals	3		process	1
	algorithms	2		economic	1
	alternatives	1		meeting	1
	design	1		documentation	1
	solutions	1		arguments	1
	functions	1		evidence	1
	models	1		feedback	1
	Analysis	1	To Choose (Total design activities=41)	alternatives	5
	codes	1		design	4
	technology	1		options	3
	laws	1		solutions	3
	patterns	1		approach	3
	math	1		team	2
	skills	1		materials	2
	standards	1		components	2
	process	1		concept	2
	simulation	1		method	2
To Compute (Total design activities=36)	results	4		process	2
	solutions	3		leader	1
	time	2		definition	1
	data	2		time frame	1
	life	2		topology	1
	stress	2		power converter	1
	temperature	2		methodology	1
	needs	1		physics	1
	failure	1		simplicity	1
	models	1		equipment	1
	values	1		best	1
	mathematical expressions	1		algorithms	1
	parameters	1	To Illustrate (Total design activities=33)	concept	6
	cost	1		design	2
	tonnage-grade	1		solutions	2
	energy balance	1		functions	2
	probability	1		behaviors	2

Verbs	**Nouns**	**Design activities**	**Verbs**	**Nouns**	**Design activities**
	algorithms	1		operation	2
	load	1		alternatives	1
	losses	1		ideas	1
	inputs	1		requirements	1
	expression	1		possibilities	1
	matlab	1		issues	1
	tonnage	1		complexity	1
	factors of safety	1		problem	1
	strain	1		structure	1
To Modify (Total design activities=38)	design	10		results	1
	prototype	2		interactions	1
	process	2		prototype	1
	options	1		reserve	1
	constraints	1		method	1
	ideas	1		example	1
	schedule	1		process	1
	practices	1		relations	1
	needs	1		summary	1
	product	1	To Practice (Total design activities=33)	design	3
	system	1		professionalism	3
	assumptions	1		engineering	3
	codes	1		ethics	2
	components	1		discipline	2
	parameters	1		process	2
	test	1		learning	1
	manufacturing	1		listening	1
	software	1		failure	1
	plan	1		teamwork	1
	concept	1		models	1
	load	1		Analysis	1
	parts	1		techniques	1
	range	1		approach	1
	iteration	1		judgement	1
	inputs	1		prototype	1
	shape	1		method	1
	storage	1		performance	1

Verbs	**Nouns**	**Design activities**	**Verbs**	**Nouns**	**Design activities**
To Solve (Total design activities=38)	problem	26		reports	1
	equation	4		changes	1
	needs	1		tool	1
	requirements	1		iteration	1
	issues	1		ethically	1
	Analysis	1		use	1
	contradictions	1	To Analyze (Total design activities=41)	data	4
	conflicts	1		problem	4
	details	1		design	2
	delay	1		information	2
To Calculate (Total design activities=39)	parameters	4		structure	2
	stress	4		sub-system	2
	load	3		method	2
	performance	3		load	2
	solutions	2		alternatives	1
	values	2		ideas	1
	cost	2		requirements	1
	options	1		application	1
	time	1		solutions	1
	data	1		system	1
	risks	1		materials	1
	system	1		models	1
	Analysis	1		results	1
	variables	1		variables	1
	components	1		topology	1
	mathematical expressions	1		behaviors	1
	physics	1		physics	1
	reaction	1		finding	1
	flash	1		plan	1
	errors	1		performance	1
	range	1		properties	1
	expression	1		process	1
	quantity	1		stability	1
	temperature	1		manufacturability	1
	displacement	1		economic	1
	strain	1	To Comp	alternatives	6

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
To Criticize (Total design activities=32)	design	7		design	4
	choice	3		solutions	4
	options	2		options	2
	decisions	2		outcome	2
	assumptions	2		results	2
	ideas	1		choice	2
	data	1		concept	2
	solutions	1		method	2
	objective	1		performance	2
	definition	1		features	1
	problem	1		system	1
	results	1		differences	1
	approach	1		pros and cons	1
	pitfalls	1		approach	1
	finding	1		aspects	1
	method	1		equipment	1
	efficiency	1		decision matrix	1
	implementations	1		properties	1
	work	1	To infer (Total design activities=33)	data	2
	arguments	1		needs	2
	inspection	1		connections	2
To Model (Total design activities=37)	system	8		conclusion	2
	behaviors	6		condition	1
	concept	3		ideas	1
	solutions	2		design	1
	components	2		solutions	1
	process	2		system	1
	failure	1		information	1
	problem	1		benefits	1
	professionalism	1		functions	1
	structure	1		limitations	1
	physics	1		phases	1
	hydrogeology	1		preference	1
	software	1		Analysis	1
	equilibrium	1		feasibility	1
	circuit	1		knowledge	1

Verbs	**Nouns**	**Design activities**	**Verbs**	**Nouns**	**Design activities**
	stress	1		behaviors	1
	flow	1		pitfalls	1
	create	1		concept	1
	3d model	1		parts	1
	relations	1		path	1
To Combine (Total design activities=36)	ideas	3		mechanisms	1
	components	3		relations	1
	sub-system	3		drawbacks	1
	solutions	2		meaning	1
	techniques	2		reasonableness	1
	knowledge	2		unknowns	1
	aspects	2	To Test (Total design activities=41)	prototype	5
	method	2		ideas	4
	load	2		hypothesis	3
	alternatives	1		design	2
	constraints	1		solutions	2
	data	1		functions	2
	practices	1		models	2
	efforts	1		assumptions	2
	possibilities	1		components	2
	stages	1		plan	2
	results	1		failure	1
	technology	1		system	1
	discipline	1		materials	1
	separate	1		codes	1
	waste	1		sub-system	1
	terms	1		software	1
	forces	1		reactor	1
	displacement	1		circuit	1
To Create (Total design activities=41)	solutions	7		response	1
	prototype	4		performance	1
	process	4		properties	1
	design	3		quality	1
	product	3		consequences	1
	ideas	2		student	1
	plan	2		workability	1

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	opportunity	1	To Design (Total design activities=34)	solutions	4
	team	1		system	4
	schedule	1		prototype	3
	database	1		materials	2
	materials	1		components	2
	models	1		process	2
	company	1		project	1
	software	1		needs	1
	concept	1		requirements	1
	diagram	1		client	1
	formula	1		product	1
	relations	1		mill	1
	blockmodel	1		engine	1
	economic	1		sub-system	1
	documentation	1		equipment	1
	innovation	1		software	1
To Develop (Total design activities=32)	ideas	4		dams	1
	solutions	4		method	1
	process	4		reactor	1
	plan	3		mechanisms	1
	alternatives	2		iteration	1
	design	2		plant	1
	product	2		society	1
	criteria	1	To Generate (Total design activities=37)	ideas	8
	definition	1		data	3
	functions	1		solutions	3
	road map	1		options	2
	methodology	1		alternatives	2
	strategy	1		electricity	2
	software	1		models	2
	concept	1		concept	2
	algorithms	1		drawings	2
	packaging	1		possibilities	1
	network	1		outcome	1
To Prepare (Total design	reports	9		results	1
	presentations	2		assignment	1
	test	2		diagram	1

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	plan	2		flow	1
	samples	2		reports	1
	drawings	2		process	1
	documentation	2		blockmodel	1
	list	2		economic	1
	schedule	1		cash flow	1
	data	1	To Synthesize (Total design activities=34)	solutions	5
	possibilities	1		ideas	3
	solutions	1		data	3
	chart	1		process	3
	problem	1		options	1
	concept	1		alternatives	1
	exam	1		practices	1
	people	1		requirements	1
	meaning	1		product	1
	poster	1		information	1
	datasheets	1		materials	1
	evaluation	1		stages	1
	cake	1		results	1
	salad	1		components	1
To Conclude (Total design activities=32)	project	5		theory	1
	solutions	2		knowledge	1
	decisions	2		essentials	1
	finding	2		group	1
	options	1		concept	1
	design	1		circuit	1
	causes	1		fundamentals	1
	selection	1		reports	1
	problem	1		polymers	1
	results	1		diagnostics	1
	feasibility	1	To Defend (Total design activities=40)	solutions	5
	choice	1		choice	5
	agreement	1		ideas	2
	best	1		design	2
	work	1		reasoning	2
	acceptability	1		decisions	2

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	performance	1		finding	2
	Profit	1		proposal	2
	reports	1		philosophy	1
	paper	1		alternatives	1
	closure	1		outcome	1
	applicability	1		system	1
	search	1		selection	1
	retrospectives	1		stages	1
	study	1		problem	1
To Evaluate (Total design activities=38)	solutions	5		results	1
	performance	5		advantage	1
	options	2		approach	1
	data	2		intuition	1
	design	2		position	1
	cost	2		reports	1
	properties	2		conclusion	1
	reports	2		thesis	1
	opportunity	1		recommendation	1
	members	1		claims	1
	specifications	1		chapter	1
	functions	1	To Explain (Total design activities=37)	decisions	3
	sustainability	1		choice	3
	feasibility	1		thoughts	2
	choice	1		ideas	2
	interactions	1		assumptions	2
	finding	1		results	2
	reserve	1		plan	2
	concept	1		concept	2
	step	1		mechanisms	2
	effectiveness	1		operation	2
	response	1		data	1
	Profit	1		needs	1
	compliance	1		client	1
To Justify (Total design	choice	8		product	1
	decisions	6		complexity	1
	approach	3		rationale	1

Verbs	Nouns	Design activities	Verbs	Nouns	Design activities
	cost	3		Analysis	1
	needs	2		structure	1
	solutions	2		activity	1
	assumptions	2		principles	1
	alternatives	1		method	1
	design	1		work	1
	complexity	1		sequence	1
	reasoning	1		conclusion	1
	hypothesis	1		expenditures	1
	results	1	To Predict (Total design activities=35)	outcome	4
	topology	1		failure	3
	method	1		behaviors	3
	mechanisms	1		future	2
	process	1		results	2
	conclusion	1		market	2
	arguments	1		cost	2
To Interpret (Total design activities=37)	results	11		performance	2
	data	5		risks	1
	requirements	3		solutions	1
	needs	2		system	1
	ideas	1		cut-off	1
	solutions	1		problem	1
	failure	1		feasibility	1
	challenges	1		variables	1
	specifications	1		advantage	1
	Analysis	1		trends	1
	behaviors	1		reserve	1
	finding	1		drawbacks	1
	environmental impact	1		deformations	1
	suggestions	1		defects	1
	statistics	1		reliability	1
	saying	1		uncertainty	1
	reports	1			
	ambiguity	1			
	drawings	1			
	meaning	1			

A.2. Noun frequencies table

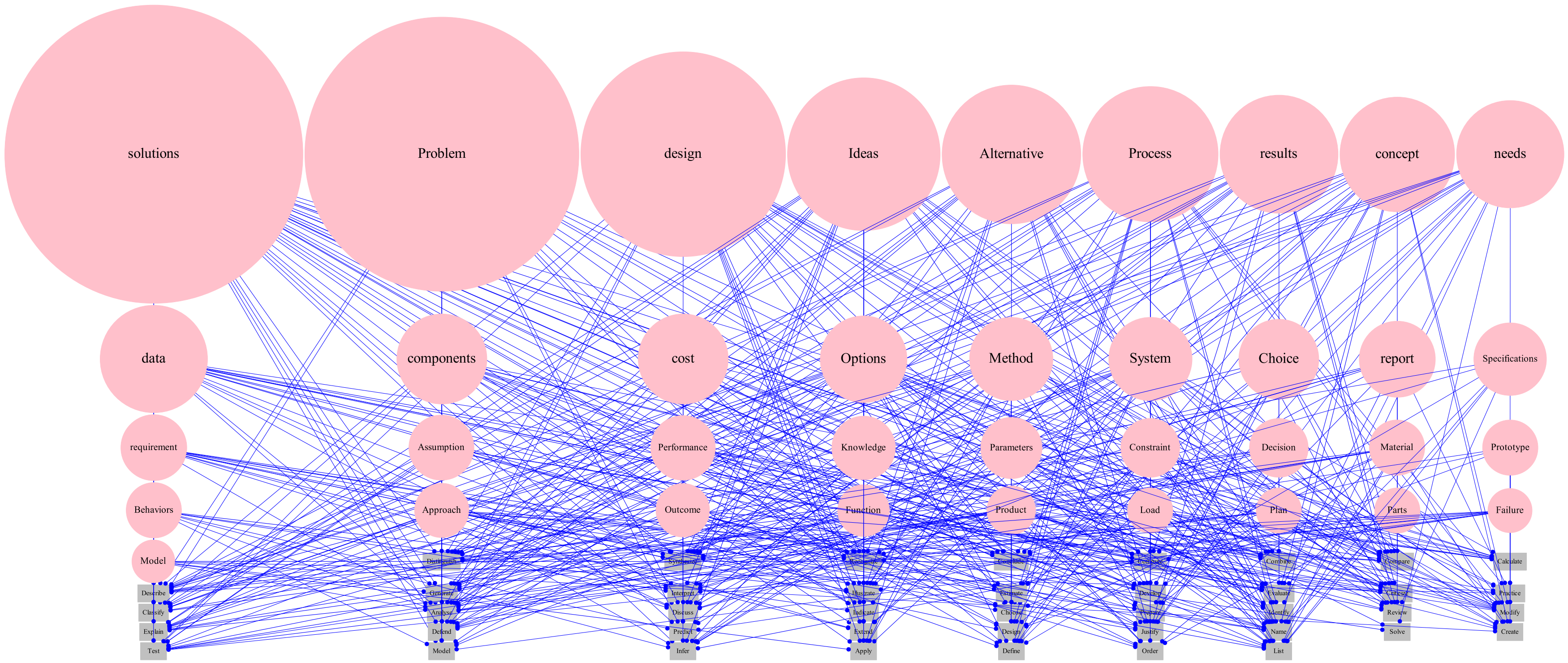
Sr.#	Nouns	Total sum of nouns	Sr.#	Nouns	Total sum of nouns
1	solutions	86	43	codes	8
2	problem	79	44	finding	8
3	design	59	45	sub-system	8
4	ideas	44	46	equipment	8
5	alternatives	40	47	time	7
6	process	39	48	limitations	7
7	results	34	49	structure	7
8	concept	33	50	advantage	7
9	data	31	51	software	7
10	needs	31	52	stress	7
11	components	26	53	drawings	7
12	cost	26	54	schedule	6
13	options	25	55	challenges	6
14	system	24	56	stages	6
15	method	24	57	priorities	6
16	choice	23	58	scope	6
17	reports	22	59	values	6
18	requirements	19	60	physics	6
19	decisions	17	61	errors	6
20	performance	17	62	properties	6
21	materials	16	63	mechanisms	6
22	behaviors	16	64	relations	6
23	prototype	16	65	meaning	6
24	approach	15	66	issues	5
25	product	14	67	objective	5
26	plan	13	68	benefits	5
27	load	13	69	feasibility	5
28	parts	13	70	principles	5
29	specifications	12	71	algorithms	5
30	functions	12	72	conclusion	5
31	constraints	11	73	operation	5
32	failure	11	74	tasks	4
33	assumptions	11	75	literature	4
34	outcome	10	76	efforts	4
35	models	10	77	leader	4
36	knowledge	10	78	definition	4
37	parameters	10	79	information	4
38	possibilities	9	80	reasoning	4

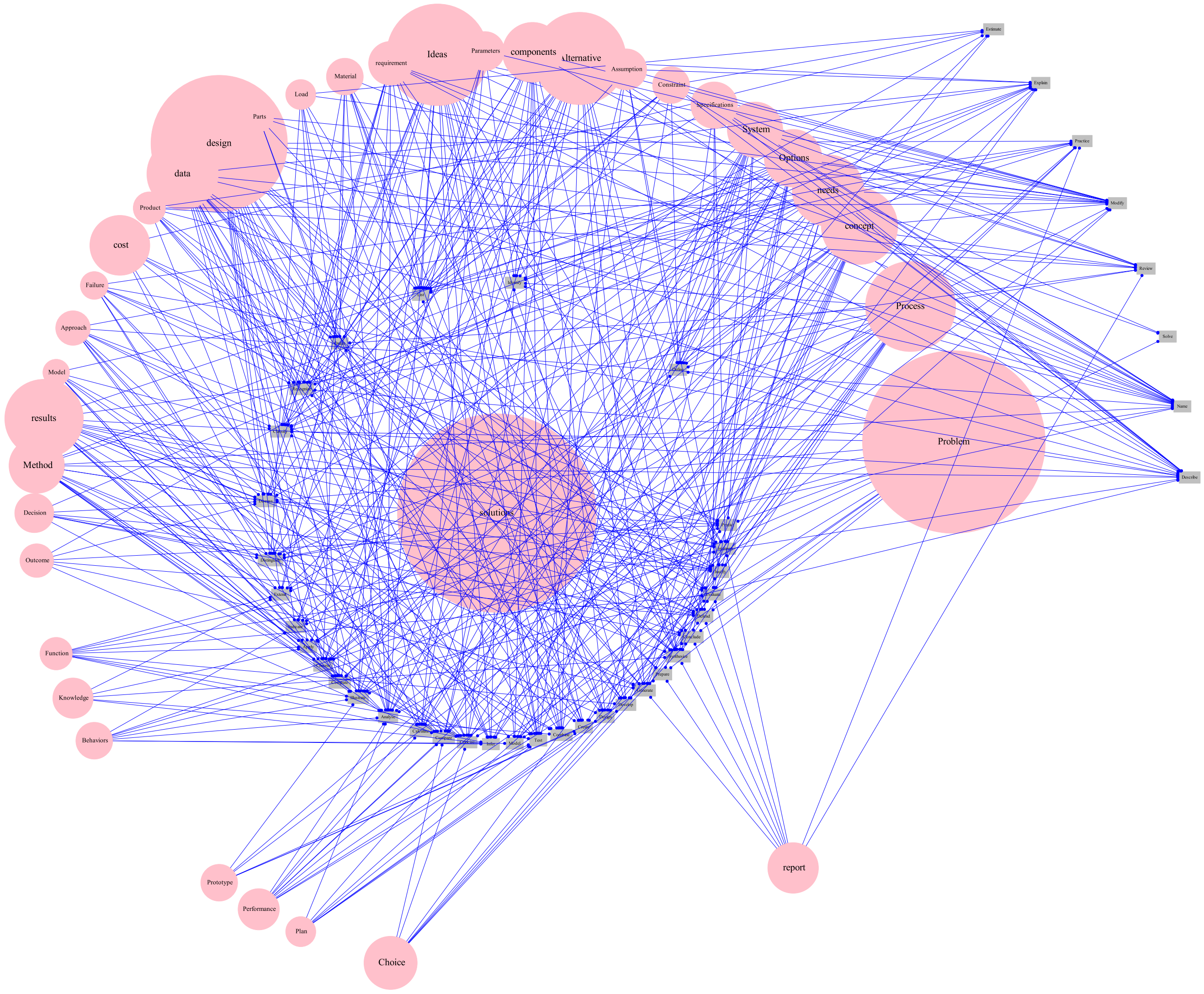
39	Analysis	9	81	selection	4
40	opportunity	8	82	life	4
41	project	8	83	professionalism	4
42	variables	8	84	hypothesis	4
85	differences	4	127	causes	2
86	topology	4	128	resources	2
87	equation	4	129	chart	2
88	discipline	4	130	time frame	2
89	weakness	4	131	presentations	2
90	test	4	132	ethics	2
91	aspects	4	133	rationale	2
92	fundamentals	4	134	future	2
93	economic	4	135	preference	2
94	documentation	4	136	flaws	2
95	thoughts	3	137	technology	2
96	team	3	138	areas	2
97	practices	3	139	methodology	2
98	risks	3	140	case	2
99	application	3	141	connections	2
100	complexity	3	142	trends	2
101	teamwork	3	143	pitfalls	2
102	goals	3	144	mathematical expressions	2
103	company	3	145	interactions	2
104	techniques	3	146	market	2
105	pros and cons	3	147	tonnage-grade	2
106	engineering	3	148	best	2
107	reserve	3	149	direction	2
108	circuit	3	150	waste	2
109	work	3	151	reactor	2
110	path	3	152	assignment	2
111	strength	3	153	efficiency	2
112	Profit	3	154	diagram	2
113	paper	3	155	patterns	2
114	iteration	3	156	skills	2
115	calculations	3	157	samples	2
116	temperature	3	158	response	2
117	drawbacks	3	159	deadlines	2
118	arguments	3	160	flow	2
119	list	3	161	proposal	2
120	features	2	162	decision matrix	2
121	criteria	2	163	standards	2

122	roles	2	164	descriptions	2
123	electricity	2	165	tool	2
124	potential	2	166	range	2
125	members	2	167	inputs	2
126	client	2	168	expression	2
169	BOM	2	211	strategy	1
170	blockmodel	2	212	sub section	1
171	closure	2	213	group	1
172	displacement	2	214	separate	1
173	supplies	2	215	environmental impact	1
174	importance	2	216	commitment	1
175	bug	2	217	suggestions	1
176	strain	2	218	position	1
177	use	2	219	justification	1
178	philosophy	1	220	manufacturing	1
179	condition	1	221	hydrogeology	1
180	learning	1	222	investigation	1
181	users	1	223	dams	1
182	listening	1	224	size	1
183	statement	1	225	energy balance	1
184	mill	1	226	equilibrium	1
185	database	1	227	reaction	1
186	timelines	1	228	flash	1
187	hazards	1	229	step	1
188	collaboration	1	230	effectiveness	1
189	phases	1	231	mistakes	1
190	cut-off	1	232	probability	1
191	management	1	233	characterization	1
192	engine	1	234	implementations	1
193	road map	1	235	classes	1
194	sustainability	1	236	math	1
195	responsibilities	1	237	suppliers	1
196	activity	1	238	relevance	1
197	soils	1	239	acceptability	1
198	power converter	1	240	losses	1
199	objects	1	241	statistics	1
200	theory	1	242	create	1
201	judgement	1	243	scenario	1
202	facts	1	244	3d model	1
203	contradictions	1	245	saying	1
204	essentials	1	246	synergies	1

205	intuition	1	247	regulations	1
206	laws	1	248	example	1
207	agreement	1	249	conflicts	1
208	nice-to-have	1	250	things	1
209	simplicity	1	251	framework	1
210	attributes	1	252	changes	1
253	exam	1	295	shape	1
254	packaging	1	296	simulation	1
255	details	1	297	uncertainty	1
256	ambiguity	1	298	invention	1
257	people	1	299	compliance	1
258	terms	1	300	delay	1
259	weight	1	301	storage	1
260	stability	1	302	inspection	1
261	forces	1	303	engineer	1
262	formula	1	304	unknowns	1
263	matlab	1	305	workability	1
264	quantity	1	306	poster	1
265	manufacturability	1	307	innovation	1
266	support	1	308	retrospectives	1
267	polymers	1	309	investors	1
268	network	1	310	datasheets	1
269	tonnage	1	311	claims	1
270	sequence	1	312	society	1
271	plant	1	313	study	1
272	factors of safety	1	314	expenditures	1
273	representative	1	315	feedback	1
274	applicability	1	316	chapter	1
275	meeting	1	317	evaluation	1
276	search	1	318	cash flow	1
277	quality	1	319	diagnostics	1
278	consequences	1	320	shortcoming	1
279	deformations	1	321	satisfaction	1
280	defects	1	288	financials	1
281	summary	1	289	optimum	1
282	student	1	290	anomalies	1
283	thesis	1	291	controls	1
284	deficiency	1	292	improvement	1
285	reliability	1	293	ethically	1
286	recommendation	1	294	reasonableness	1
287	evidence	1			

A.3. Design activities network




Ideas
Parameters
components
Alternative
requirement
Assumption
Material
Constraint
Load
Specifications
Parts
System
design
Options
data
needs
Product
concept
cost
Failure
Process
Approach
Model
results
Problem
Method
solutions
Decision
Outcome
Function
Knowledge
Behaviors
Prototype
Performance
Plan
Choice
report
Estimate
Explain
Practice
Modify
Review
Solve
Name
Describe
List
Identify
Define
Order
Recognize
Classify
Discuss
Distinguish
Extend
Indicate
Apply
Choose
Compute
Illustrate
Analyse
Calculate
Compare
Criticize
Infer
Model
Test
Combine
Create
Design
Develop
Generate
Prepare
Synthesize
Conclude
Defend
Evaluate
Justify
Interpret
Predict

A.4. Design stages comparison

Game Results (by participants)			Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
Participant sr #	Department	Discipline						
s1	Game sheet stages		Problem definition, planning, functional and technical specification	Conceptual design		Detailed design (manufacturing, assembly, testing)	Testing and Refinement	Final Production
	Pre-game stages		problem definition and solution specifications	conceptual design		detailed design		
s2	Game sheet stages		Brainstorming and literature review	Decision matrix	Detailed design	Detailed design: iteration and integration	Building of the design and preliminary testing	Final production, testing
	Pre-game stages		define problem specifications requirements brainstorming and literature review	concept selection and decision matrix		detailed design and calculations	prototyping	iteration
s3	Game sheet stages		Design constrains set by owner	Desktop design study	Site characterization	Determine loads, safety factors, design option	Detailed calculations for suitable options, costs, schedules	Final Report
	Pre-game stages		establish a need design constraints loading systems load calculation	site investigation and soil characteristics	estimate loading on structure	calculations to design retaining structures	cost estimation	schedule determine factor of safety
s4	Game sheet stages		Drillhole data location	Collecting required information for each chapter	Preparing each chapter based on Canadian standards	Detail design	Economic and contingency plan for final decision	Preparing final report to present
	Pre-game stages		population/culture/style review problem definition find an approach review Canadian (local) codes and standards	data analysis	solution			report (chapter) production
s5	Game sheet stages		project planning	creative synthesis and concept evaluation/selection	system design	detailed design and analysis	prototyping and testing analysis	prototyping
	Pre-game stages		Project planning criteria specifications and creative synthesis	concept development and evaluation Selection of final concept			testing and analysis	prototyping
s6	Game sheet stages		establishing objectives and specifications	develop 3 designs and deciscion matrix	preliminary calculations	higher level calulations and modeling	prototype testing / subsystem testing	design for manufacturing
	Pre-game stages		establish objective specifications	developing 3d design and choosing one			design refinement;testing and cost analysis	
s7	Game sheet stages		Planning	Concept development	feasibility	Detail Design	construction and operation	closure
	Pre-game stages		material characterization volume calculation	stress and strength calculation seepage calculation	structure evaluation for physical integrity of deposits water balances evaluation	effects and errors and failure modes evaluation		
s9	Game sheet stages		define problem and planning	Concept development	System-level Design	Detail Design	simulation, testing, optimization	Final Production
	Pre-game stages							
s10	Game sheet stages		customer requirements and constrain identification	Concept development	System-level Design	design and optimization	experiemntal validation	Final Production
	Pre-game stages							
s11	Game sheet stages		define the problem, design accornding to clients needs	group formation, brainstorming, specification definitions	2-3 design alternatives, report, MT report	Detail Design	prototyping and testing	final stage
	Pre-game stages		problem definition (client's needs) generate ideas and brainstorming	design options evaluation (matrix spec table)		detailed design (choice; costs; generate 1-2 designs; choose one & finalize)	physical prototype	analysis report building (prototype)
s13	Game sheet stages		scope definition, schedule defintiion	use of tools, visualization, animation	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		know relevant code and regulations limits and boundaries practical aspects	conceptual design	specifics of the design present the project			
s15	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		exploratory development	evaluation				
s16	Game sheet stages		defining a problem	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		defining problem find bottleneck	knowledge to troubleshooting				
s17	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages							
s19	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		objective definition generate possible solutions	select single solutions evaluate solution and analysis	estimated output and comparison with ideal objective			
s20	Game sheet stages		problem definition, requirements	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages							
s21	Game sheet stages		requirements	architecture	design	implementation	testing	release
	Pre-game stages		problem definition problem analysis	idea diagrams	design	detailed design	testing	implementation coding iterations
s22	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		problem definition; check constraints and specs preliminary design			technical (detailed calculations) design	final report (testing and drawing production)	
s23	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		problem definition and choice of tools matarial processing and background	macro analysis			material testing	
s24	Game sheet stages		explore	conceptual design	System-level Design	Detail Design	validation	commisioning, Start up
	Pre-game stages		objective explore	appraise select	define execute	operate		
s25	Game sheet stages		road map	Concept development	System-level Design	Detail Design	Testing and Refinement	assembly and production
	Pre-game stages							
s27	Game sheet stages		exploration, problem identification	identification of possible solutions	design for X, specs, constraints	embodiement	design analysis, testing, prototyping, revising, refining	detailed design, production
	Pre-game stages		discover define	develop deliver				
s28	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production
	Pre-game stages		conceptual report (problem definition; management and brainstorming; specs; planning)		analysis report (technical analysis of components and sub-system)	final report (iteration and improvement)		
s29	Game sheet stages		market research	Concept development	System-level Design	Detail Design	mplementation and test	Final Production
	Pre-game stages							
s30	Game sheet stages		project scope and specs development	Concept development	conceptual development	Detail Design	CAE analysis	
	Pre-game stages		customer requirement collection	concept design		detailed design		prototyping and production
s31	Game sheet stages		problem definition	Concept development	System-level Design	Detail Design	Testing and Refinement	Manufacturing
	Pre-game stages		task clarification	conceptual design	embodiment design	detailed design		
s32	Game sheet stages		Planning	Concept development	System-level Design	Detail Design	Testing and Refinement	Final Production

	Pre-game stages												
s34	Game sheet stages	project management				requirement specification		design		Implementation		testing	Field Usage
	Pre-game stages	find client need		working to find appropriate software		prototype	feedback					refinement	extension
No Formal Stages													
s8	Game sheet stages	Problem identification				Concept development		model / tool selection		parameter selection		learning / tuning	Final Production
	Pre-game stages	tool identification		structure selection		parameter selection							
s12	Game sheet stages	Planning				Concept development		System-level Design		Detail Design		Testing and Refinement	Final Production
	Pre-game stages	problem definition		finding relevant variables		get reasonable number for each variable	try with number if it works	verify and optimize					
s14	Game sheet stages	network planning and screening				diagnostics		remedy		economic assessment		priority check	evaluation
	Pre-game stages	analyze problem		understand data		generate solution	evaluate solution						
s18	Game sheet stages	Planning				Concept development		System-level Design		Detail Design		Testing and Refinement	Final Production
	Pre-game stages	assess the system		select or identify material and its strength						stepwise detailed calculations		work with 1 solution	
s26	Game sheet stages	Planning				Concept development		System-level Design		Detail Design		Testing and Refinement	Final Production
	Pre-game stages	problem formulation		data collection		equations and stress level	comparing with actual conditions	re-select materials					
s33	Game sheet stages	Planning				Concept development		System-level Design		Detail Design		Testing and Refinement	Final Production
	Pre-game stages	introductory survey course for circuits		what; why and how to apply		fundamentals	definition	application					

A.5. Ontology for six-stage design process