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Original citation:
Butt, M, Sharunova, A, Storga, M, Khan, YI & Qureshi, AJ 2018, 'Transdisciplinary Engineering Design Education Ontology for a Generic Product Design Process' *Procedia CIRP*, vol 70, pp. 338-343.
https://dx.doi.org/10.1016/j.procir.2018.02.019

DOI 10.1016/j.procir.2018.02.019
ISSN 2212-8271

Publisher: Elsevier

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 70 (2018) 338–343

www.elsevier.com/locate/procedia

28th CIRP Design Conference, May 2018, Nantes, France

Transdisciplinary Engineering Design Education: Ontology for a Generic Product Design Process

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Abstract

Today's highly integrated product development practices emphasize the need to transform the engineering education from disciplinary to transdisciplinary. This paper is based on the results of an empirical study designed to introduce a common transdisciplinary design process in engineering education. 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. It proposes a high-level transdisciplinary engineering design process that consolidates a diverse array of engineering terms and concepts into a generalized model.

Peer-review under responsibility of the scientific committee of the 28th CIRP Design Conference 2018.

Keywords: Design; Process; Transdisciplinary Engineering Design; Transdisciplinary Engineering Design Education Ontology; Taxonomy.

1. Introduction

Design is a fundamental concept in engineering education. Design and engineering design process serve as a common thread that ties engineering disciplines together [1]. 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 [2-6]. 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 shows some engineering design processes/stages followed by individual 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.) results in challenges 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 [11,12].

One way to develop the concept of transdisciplinarity in education is through the presentation of common 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 [13].

2212-8271
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Table 1. Common engineering design stages [7-10,23,24].

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
RIBA	Preparation	Design	Pre-construction	Construction	Use	Preparation
Jansch et all	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

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. 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 [21,22]. 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 [14]. 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 [15].

1.1. 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:

- 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?
- 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. 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 Fig.1. These stages were: *planning, data collection, terminology identification, categorization, formalization and implementation, refinement* and *documentation*. The activities performed during each stage are described below.

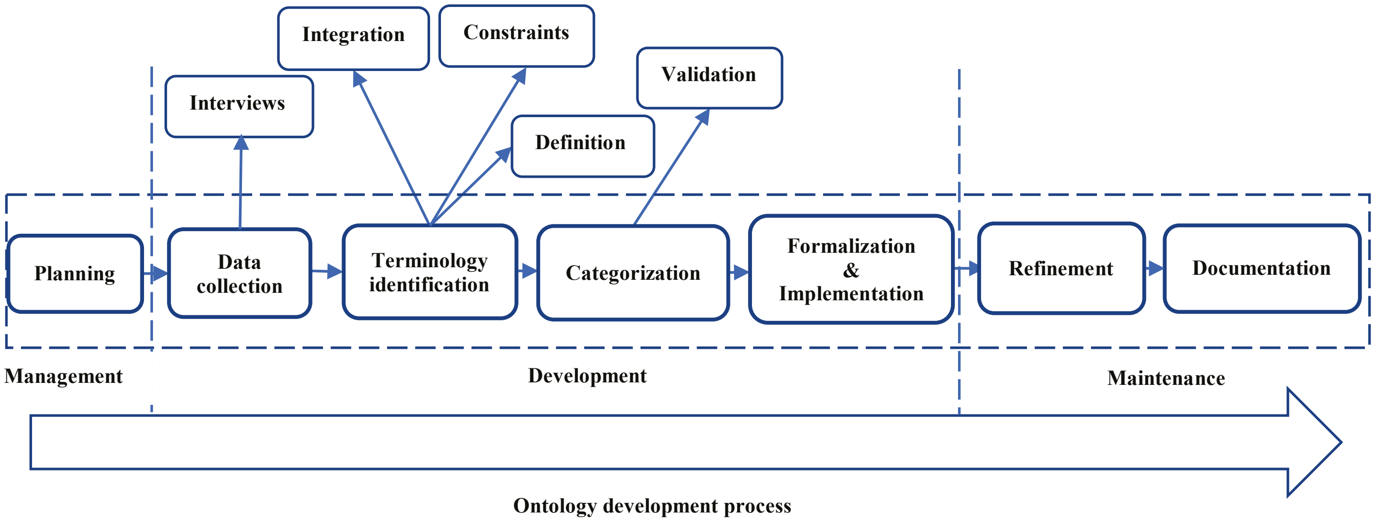

Fig 1. TEDEO development process.

2.1. 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.

2.2. Data collection

The data collection stage consisted of 34 individual interviews carried out with engineering professors from various 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 an 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 [8]. The process was chosen based on current research on transdisciplinary engineering design process [2,4,5,6] 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 identify with the most commonly used design stages of their own specific discipline. They were also asked to map their engineering design stages over the given six stage design process. The results of this specific activity paper are subject of a separate research paper.

In the next stage, each participant was given 42 randomly mixed verbs, taken from 6 cognitive domains of Bloom's Taxonomy (7 unique verbs from each of the six cognitive levels) [14,16]. Participants were asked to come up with a related noun for each verb. Participants were allowed to use the same noun more than once if they choose to.

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

2.3. 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 Standard Upper Merged Ontology (SUMO) 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 [15].

A detailed study about the classification of entities in engineering design domain was done by Storga et al. [15,17] which we used as the foundation of TEDEO. An overview of the top-level categorization is given in Fig.2a [18]. Fig. 2b shows the project-specific top-level classes and their subsequent subclasses that are described in the next section.

2.4. Categorization

Once the nouns were defined, the next stage was building the taxonomy for the ontology. The categorization places nouns into different categories 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 [15]. 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 (http://www.adampease.org/OP/) and summarized below with examples.

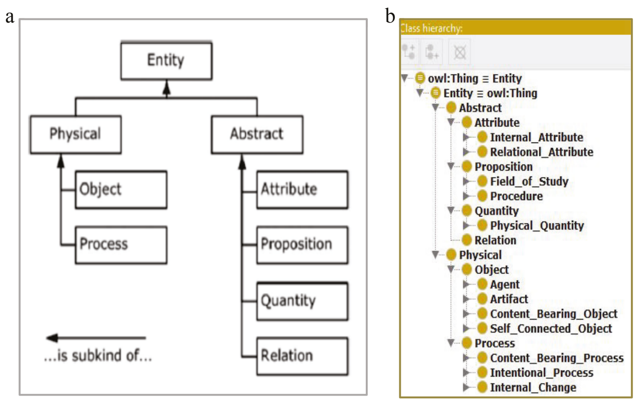

Fig.2. (a) SUMO Classification; (b) TEDEO top level classes

The *Object* corresponds roughly to the class of ordinary objects. 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 *Content Bearing Process* is a subclass of the process, which involves the content of information. In Intentional process, 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 Science and Mechanical Engineering respectively. Leader and User in social role as proposed by participants from Electrical and Computer Science 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.

2.1. 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 reliability by measuring the observed agreement between the coders and subtracting any agreement that occurred by chance [19,20]. Once the categorization was done, experts from the relevant research area analyzed the definitions and categorized the terms independently. Their input was compared to the previous categorization to check the reliability. Depending on the value of Kappa coefficient from 0 (lowest) to 1 (highest), 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

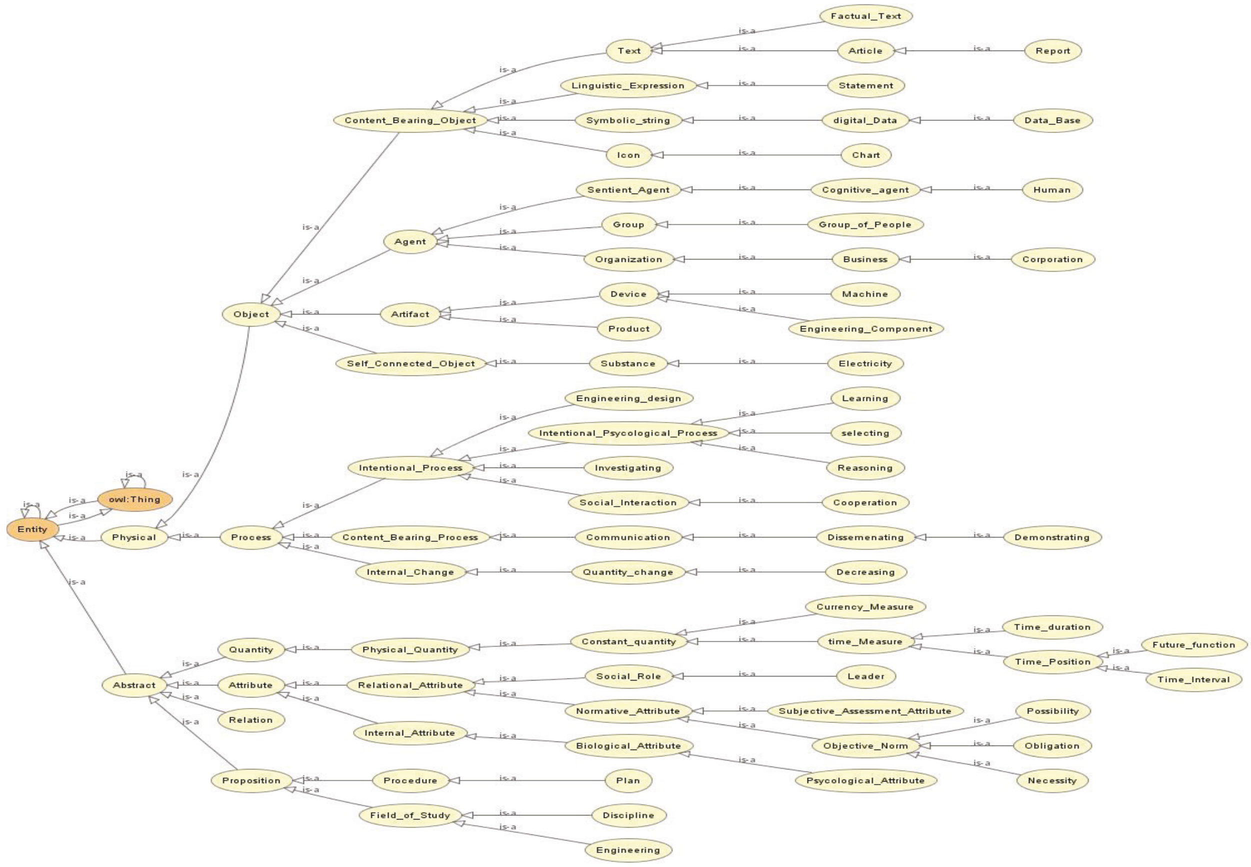

Fig.3. TEDEO class structure.

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.

2.2. Formalization & implementation

The next step after validation is the ontology formalization and implementation, which includes taxonomy building. The tool used for building the taxonomy is Protégé. Protégé is an open source tool developed at Stanford University (https://protege.stanford.edu/) that has a large community of users. The reason for using Protégé in this research project is 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, which are most specialized concepts of a knowledge database. The complete taxonomy for the first design stage with 101 entities is shown in Fig. 3. 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 our 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 2.4. Fig. 4 represents a small section of objects related through properties defined for them.

3. 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, we showed the results for the first design stage of a transdisciplinary engineering design process, which support our 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:

- 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.

- 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.

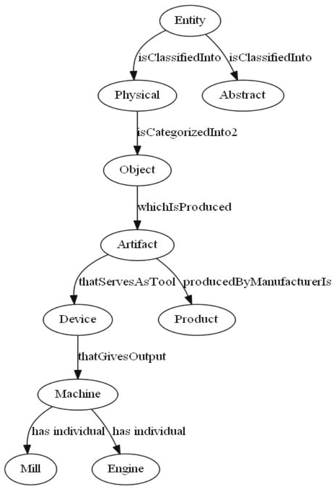

Fig.4. Visualization of *Artifact.*

The next step of this research project is to analyse 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 an engineer with transdisciplinary approach will not only understand the generic components of an engineering design process, he 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. We also believe that the generalized methodology for TEDEO is not only limited to engineering but it can also be applied in fields other than engineering.

Acknowledgements

The authors gratefully acknowledge the support of the Center for Teaching and Learning at the University of Alberta and all project collaborators: Dr. Suzanne Kresta, Dr. Jason P. Carey, Dr. Loren Wyard-Scott, Dr. Samer Adeeb, and Dr. Lucienne M. Blessing.

References

[1] Tanik, M.M., Yeh, R.T. and Ertas, A., 1995. Integrated design and process strategies SDPS. In *The First World Conference on Integrated Design and Process Technology*, Vol. 1, p. 511-514.

[2] Qureshi, A.J., Gericke, K. Blessing, L. 2013. Design process commonalities in trans-disciplinary design. In *International Conference on Engineering Design*.

[3] Gericke, K., Adolphy, S., Qureshi, A.J., Blessing, L. and Stark, R., 2013, June. Opening Up Design Methodology. In *International Workshop on the Future of Trans-Disciplinary Design*. p. 4-15.

[4] Qureshi, A.J., Gericke, K. and Blessing, L., 2014. Stages in product lifecycle: Trans-disciplinary design context. *Procedia CIRP*, *21*, p.224-229.

[5] Gericke, K., Qureshi, A.J. and Blessing, L., 2013, August. Analyzing transdisciplinary design processes in industry–an overview. In *Proceedings of the ASME 2013 International Design Engineering Technical Conference & Computers and Information in Engineering Conference (IDETC/CIE 2013). Portland, Oregon, USA*, p. 10.

[6] Gericke, K. and Blessing, L., 2012. An analysis of design process models across disciplines. In *DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia*.

[7] Kruchten, P., 2004. The rational unified process: an introduction. Addison-Wesley Professional.

[8] Eppinger, S. and Ulrich, K., 2015. *Product design and development*. McGraw-Hill Higher Education.

[9][Online] available from: https://www.architecture.com/-/media/gathercontent/riba-plan-of-work/additional documents/ribaoutlineplanofwork2007revised2008pdf.pdf

[10] Ertas, A., 2010. Undestanding transdiscipline and transdisciplinary process. *Transdiscipl J Engin Science*, *1*(1), p.55-73.

[11] Zaharim, A., Yusoff, Y., Omar, M.Z., Mohamed, A. and Muhamad, N., 2009, July. Engineering employability skills required by employers in Asia. In *Proceedings of the 6th WSEAS international conference on Engineering education*, p. 195-201.

[12] Sharunova, A., Butt, M., Kresta, S., Carey, J., Wyard-Scott, L., Adeeb, S., Blessing, L. and Qureshi, A.J., Cognition and Transdisciplinary Design: An Educational Framework for Undergraduate Engineering Design Curriculum Development. *engineering education*, *16*, p.27.

[13] Ertas, A., Maxwell, T., Rainey, V.P. and Tanik, M.M., 2003. Transformation of higher education: the transdisciplinary approach in engineering. *IEEE Transactions on Education*, *46*(2), p.289-295.

[14] *New York University Steinhardt*, 2017. [Online] Available from: https://steinhardt.nyu.edu/scmsAdmin/media/users/VerbsforStudentLearningObjectives.pdf

[15] Štorga, M., Andreasen, M.M. and Marjanović, D., 2010. The design ontology: foundation for the design knowledge exchange and management. *Journal of Engineering Design*, *21*(4), p.427-454.

[16] Krathwohl, D.R., 2002. A revision of Bloom's taxonomy: An overview. *Theory into practice*, *41*(4), p.212-218.

[17] Storga, M., Andreasen, M.M. and Marjanovic, D., 2005. Towards a formal design model based on a genetic design model system. In *DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08. 2005*.

[18] Mario, S., Dorian, M. and Myrup, A.M., 2007. Relationships between the concepts in the design ontology. *Guidelines for a Decision Support Method Adapted to NPD Processes*.

[19] Stemler, S., 2001. An overview of content analysis. *Practical assessment, research & evaluation*, *7*(17), p.137-146.

[20] McHugh, M.L. 2012. Interrater reliability: the kappa statistic. *Biochemia medica*, *22*(3), p.276-282.

[21] Frank, M. and Waks, S., 2001. Engineering systems thinking: A multifunctional definition. Systemic Practice and Action Research, 14(3), pp.361-379.

[22] Frank, M., 2000. Engineering systems thinking and systems thinking. Systems Engineering, 3(3), pp.163-168.

[23] Jänsch, J. and Birkhofer, H., 2006. The development of the guideline VDI 2221-the change of direction. In DS 36: Proceedings DESIGN 2006, the 9th International Design Conference, Dubrovnik, Croatia.