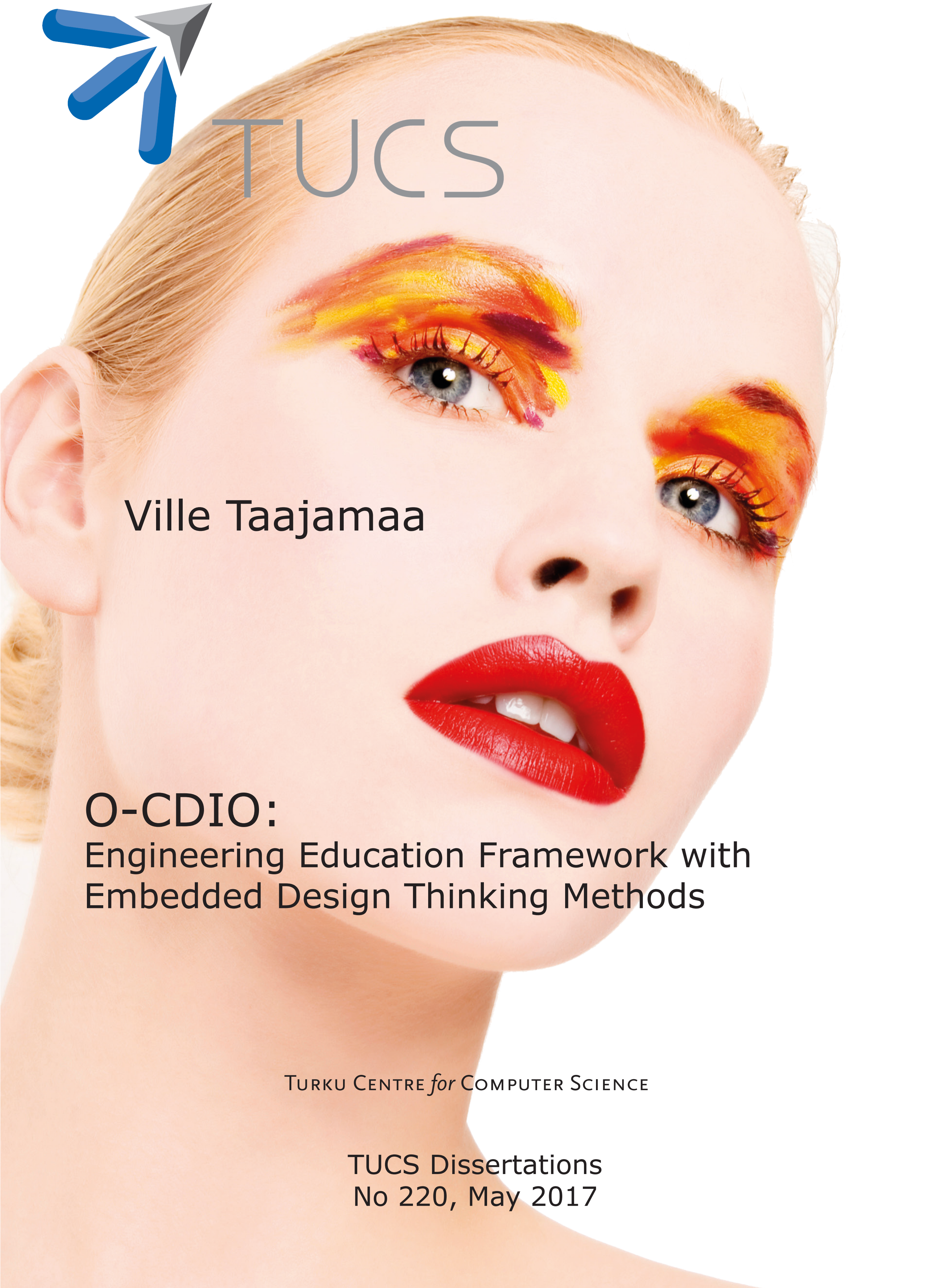

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Ville Taajamaa

O-CDIO:
Engineering Education Framework with Embedded Design Thinking Methods

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O-CDIO: Engineering Education Framework with Embedded Design Thinking Methods

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Abstract

Technology and its applications have an ever-increasing role in our daily lives. Healthcare, logistics, commerce, manufacturing, and even social interaction, all have aspects of technology embedded in them. The complexity and importance of the technical systems we use varies, yet they are becoming increasingly versatile and more important to the functionality of entire systems and their services. At the same time, the complexity of understanding the future needs of the role that technology plays in such systems and what they are supposed to deliver varies from linear to chaotic. This has had a fundamental impact on the engineering profession. The more complicated, complex or even chaotic a system is, the more innovative and cooperative an engineer needs to be. Thus, engineers also need to understand people.

This thesis presents a novel engineering education model, O-CDIO, which is based on an existing framework known as the CDIO framework. The O-CDIO model is derived from the results of the university level engineering education reform enacted in a multidisciplinary science university in Northern Europe, and from the scientific discourse within the domain of the engineering education research and literature. The timeline for the research was fall 2011 to fall 2015. The model that was developed emphasizes the need to educate engineers to become ***problem definers*** in addition to educating them to become ***problem solvers***. This can be achieved by integrating human-centered design thinking methods and challenges into engineering courses from day one to graduation.

The results of the piloted courses in the reform process show that transferable working life skills, such as communication, teamwork, problem-solving, prototyping skills, and tolerance towards ambiguity, were enhanced. These skills are widely seen as necessary for future engineering. The preliminary results also show that the courses provide an opportunity for self-discovery, increased self-efficacy, and result in an increase in entrepreneurial thinking.

There were clear limitations to this research. The piloted courses had no control groups. The reflections on and comparisons of the results were achieved by considering the results of similar studies and the literature. Although some of the courses were run for three consecutive years, this research has very little longitudinal evidence. Future research should focus on implementation of the O-CDIO model as a whole, with longitudinal research set as one of its goals.

Keywords: Engineering education, The CDIO framework, Activating teaching methods

Tiivistelmä

Teknologian rooli maailmanlaajuisesti verkottuneessa teollisuudessa ja yhteiskunnassa on merkittävä ja ennustettavissa olevan tulevaisuuden ajan myös kasvussa. Se on myös enenevissä määrin sekä monimutkainen että moniulotteinen. Terveydenhuolto, teollisuus, koulutus, liikenne, ja internet, jopa sosiaalinen kanssakäyminen ovat esimerkkejä aloista ja ilmiöistä jotka ovat jollain tavalla riippuvaisia niiden sisältämän tekniikan toimivuudesta. Samaan aikaan teknologioiden ja tekniikan roolin ymmärtäminen sen eri konteksteissa on haastavampaa. Tekniikalla ei ole itsetarkoitusta. Sen tehtävä on aina palvella. Tämä asettaa uudenlaisia haasteita diplomi-insinööreille ja heidän kouluttamiselle. Tekniikan koulutus yliopistotasolla on maailmanlaajuisesti kyennyt vastaamaan sille asetettuihin haasteisiin. Tosin lähes poikkeuksetta muutos on syntynyt ulkoisen muutostarpeen aiheuttamana. Mitä monimutkaisemmaksi ja moniulotteisemmaksi tekniikalle ja teknologioille asetetut vaatimukset kehittyvät sitä monipuolisemmaksi pitää myös koulutuksen muuttua. Tämä tutkimus ja tieteellinen raportti perustuu suomalaisessa monialayliopistossa tapahtuneeseen tekniikan koulutuksen muutosprosessiin, tuloksiin sen aikana pilotoiduista kursseista ja alan kirjallisuuteen. Tutkimuksen tuloksena syntyi tekniikan koulutuksen malli joka johdettiin edellä mainituista tutkimuksen tuloksista, olemassa olevasta tekniikan koulutusmallista nimeltä CDIO ja kirjallisuudesta. Mallin ydinidea on kouluttaa diplomi-insinööreistä *ongelmanhahmottajia ongelmanratkaisijoiden* lisäksi. Tämä tapahtuu integroimalla ihmis- ja käyttäytymistieteisiin perustuvia opettamismetodeja läpi koko koulutuksen ensimmäisestä päivästä valmistumiseen asti.

Reformin aikana tehdyt tutkimukset osoittivat että opettamismetodit saavuttivat niille asetetut oppimistavoitteet. Työelämätaidot kuten viestintä-, ryhmätyö-, ongelmanratkaisu- ja prototypointitaidot lisääntyivät. Alustavat tulokset myös osoittivat että opiskelijoiden reflektointikyky ja positiivinen suhtautuminen yrittäjyyteen lisääntyivät. Lisätutkimuksen tarve aiheeseen liittyen on ilmeinen. Tutkituissa kursseissa ei ollut mahdollista käyttää kontrolliryhmiä eikä O-CDIO mallia ole missään vaiheessa testattu kokonaisuudessaan. Lisäksi pitkän ajan vaikutuksia ei voitu tutkimuksen ajallisista kestosta johtuen testata. Pisimpään samanlaisena pysyneeltä kurssilta saatiin tutkimusaineistoa kolmelta eri vuodelta. Lisäksi tämän raportin kirjoittaja vastasi myös lähes poikkeuksetta tutkittujen kurssien ideoinnista, kehittämisestä ja opettamisesta. Tämä on otettu analyysivaiheessa huomioon mutta silti vaikuttaa tutkimustuloksiin. Luonnollinen lisätutkimuksen aihe on tutkia O-CDIO mallia kokonaisuudessaan todellisessa tekniikan koulutuksen kehyksessä ja riittävällä aikajänteellä.

Avainsanat: Tekniikan koulutus, CDIO-koulutusmalli, Aktivoivat opetusmenetelmät

Acknowledgements

A unique opportunity. That would be the best way to describe this thesis project and the university level engineering education reform behind it. Ideating, designing, implementing, assessing, analyzing and further developing a total of eight different courses and six different course formats in four different continents, in addition to consulting on other courses during the four years spent on this project, has been a rewarding experience. It has not only laid the foundation of this thesis but also changed the way I perceive the world. I owe a sincere debt of gratitude to so many people that it is impossible to mention them all here. To Dr. T. Salakoski for providing the opportunity to manage the reform process and the chance to focus on research afterwards. To Dr. H. Tenhunen and Dr. L. Toivonen for a global perspective on higher education. In gaining an understanding of teaching, I have had the opportunity to follow several inspiring personalities: Dr. B. Karanian, Mr. A. Järvi, Lic.Sc. L. Repokari, and Dr. L. Leifer gave extraordinary examples of student-centered teaching and have illuminated how emotions play a key role in transformative and holistic learning. To Dr. S. Hyrynsalmi and Ms. Anne-Maarit Majanoja whom expended considerable effort in making this document look and feel like a scientific report. To Mr. H. Sjöman, Mrs. X. Guo, Mrs. M. Eskandari, Dr. P. Liljeberg, Ms. E.Rautavaara, Dr. T. Westerlund, Mrs. S.Kirjavainen and Dr. M. Hupli for working together during the research process. The key ideas in this thesis were created in collaboration with the engineering educators at the University of Turku, Fudan University in Shanghai, and the Design Thinking community at Stanford University.

I am bewildered by the amount of patience and understanding my wife Hanna and my family have shown towards me and this project. Of the many roles in life, being a father is the one in which there is no room for compromise. And forward we go!

I end with the words that kept me going when I wanted to stop.

"In silence, in steadiness, in severe abstraction let him hold by himself; add observation to observation, patient of neglect, patient of reproach; and bide his own time, – happy enough, if he can satisfy himself alone, that this day he has seen something truly. Success treads on every right step. For the instinct is sure, that prompts him to tell his brother what he thinks. He then learns, that in going down into the secrets of his own mind, he has descended into the secrets of all minds. He learns that he who has mastered any law in his private thoughts, is master to that extent of all men whose language he speaks, and of all into whose language his own can be translated. The poet, in utter solitude remembering his spontaneous thoughts and recording them, is found to have recorded that, which men in crowded cities find true to them also. The orator distrusts at first the fitness of his frank confessions, – his want of knowledge of the persons he addresses, –until he finds that he is the complement of his hearers; – That they drink his words because he fulfills for them their own nature; the deeper he dives in to his privatest, secretest presentiment, to his wonder he finds, this is the most acceptable, most public, and universally true. The people delight in it; the better part of every man feels, This is my music, this is myself." (R. W. Emerson, about the duties of a scholar, year 1837) [1, p.21].

Table of Contents

List of Abbreviations

PI = Principal Investigator
O-CDIO = Observe – Conceive-Design-Implement-Operate
CDIO = Conceive-Design-Implement-Operate
UTU = University of Turku
EE = Engineering Education
EER = Engineering Education Research
HE = Higher Education
HEI = Higher Education Institute
ABET = Accreditation Board for Engineering and Technology
MOOC = Massive Open Online Course
ILO = Intended Learning Outcome
GTM = Grounded Theory Method
RDC = Radical Design Challenge
PDRP = Product Development and Rapid Prototyping
IT = Information Technology
Biotech = Biotechnology
I2E = Introduction to Engineering
ICT= Information and Communication Technology
PAR= Participatory Action Research
MM= Mixed Method
SBL=Storytelling-based learning

List of Publications in this Thesis

Publication I

V. Taajamaa, K. Vilonen, "Future trends of engineering education – implementing CDIO?", International Conference on Engineering Education 2012, Turku Finland, 2012

Publication II

V. Taajamaa, X. Guo, T. Westerlund, H. Tenhunen, T. Salakoski, "First Evolution of the Introduction to Engineering course – Case Study from the University of Turku", CDIO Conference Proceedings 2014

Publication III

V. Taajamaa, H. Sjöman, S. Kirjavainen, T. Utriainen, L. Repokari, T. Salakoski, "Dancing with Ambiguity – Design thinking in interdisciplinary engineering", Design thinking conference, Shenzhen, China, 2013

Publication IV

E. Rautavaara, V. Taajamaa, V. Lyytikainen, T. Salakoski, "Learning outcomes of a project-based capstone product development course", Norddesign Conference 2014, Finland

Publication V

A. Jarvi, V. Taajamaa, S. Hyrynsalmi, "Lean Software Startup – an Experience Report from an Entrepreneurial Software Business Course", The 6th International Conference on Software Business, Portugal 2015

Publication VI

X. Guo, V. Taajamaa, K. Yang, T. Westerlund, L. Zheng, H. Tenhunen, T. Salakoski: "CAPSTONE BOOTCAMP CONCEPT CATALYZING PROBLEM-BASED LEARNING", CDIO conference 2015

Publication VII

M. Eskandari, V. Taajamaa, B. Karanian, "Tell/Make/Engage: Design Methods Course Introduces Storytelling Based Learning", American Society for Engineering Education 2015 Conference, Seattle, USA.

Publication VIII

V. Taajamaa, M. Eskandari, B. Karanian, A. Airola, T. Pahikkala, T. Salakoski, "O-CDIO: Emphasizing Design thinking in CDIO engineering cycle", International Journal of Engineering Education Vol. 32, No. 3(B), pp. 1530–1539, 2016

1. Introduction – adding human-centered approaches to engineering education

The role of technology is increasing in our daily lives [2,3,4]. Whether it is young children using smartphones and tablets for playing games, learning or contacting home; nurses or soldiers using smart embedded systems and technologies to achieve their objectives; or an African farmer using ICT to make sure he gets the best price for his product [5]. Technology is everywhere, and connects us to everything. Engineers play a key role in creating new technologies for many different purposes, and the natural sciences are firmly embedded in the foundations of any given technology [6,7,8,9,10]. The natural sciences also create the foundation for engineering education [11]. Throughout time, engineers have solved problems from building bridges for Roman armies, to building magnetic resonance imaging, and other high technology in order to save lives [12]. It is also relevant here to mention Internet applications and the World Wide Web that have changed the way we shop, communicate and interact with each other [13]. Technology has changed the way we live our daily lives and it is not going anywhere. On the contrary, the pace of change and development is increasing all the time [13,14].

What is common to all inventions is that they are meant for someone and they serve a purpose. They do not exist without an intention. This applies to the whole of the engineering profession, and so it must apply to engineering education. It does not exist without a purpose. The objective or intent can be negotiated academically, politically or philosophically, yet there always exists a reason. All this means that engineering education has to have value, if it is to be able to serve the needs of industry, society and, in this case, students.

Another ever-increasing phenomenon is that the complexity of technical systems is becoming increasingly all-encompassing, and simultaneously those systems are becoming so small in size that it is difficult to comprehend them [15]. How is it possible to manage an urban environment using ICT to control traffic, buildings, hospitals, homes, cars, and everything in between? How can we construct, monitor, and develop nanoscale drugs with sensors and other biotechnical innovations? It is a tall order for an engineer to comprehend and manage the complexity of the technical world and create products that are able to serve all the needs of the plethora of possible users. And especially difficult to do so when using mathematics, physics, chemistry, biology and the other natural sciences as tools, and working only with other engineers. Hence, it is clear that although the natural sciences are the foundation of engineering, knowledge of only them is not enough. There is a clear and present need to understand the

people that use technology and to identify needs that no one knew existed. And to do that, there is a need to work together with people from other disciplines and walks of life [16-19]. The identification of the problem space is just as important as the ability to solve the given problem. And when the problems become more complex and holistic so must the palette of the needfinding and problem-solving tools [20,21]. In engineering education, this means adapting human-centered approaches and the methods of needfinding and solving –
in addition to using the approaches and methods from the natural sciences [20,22,23]. Not forgetting the final and the most important goal of any profession or education: to preserve our environment and to serve humanity in all of its variations.

The abovementioned approach presents the underlying rationale, theme and purpose of this thesis. It also applies to the O-CDIO engineering education model that was created as part of the thesis research, presented in Figure 1. The reform of engineering education at the University of Turku, and the process of research related to that have been resulted in a model that integrates the natural sciences with human-centered design thinking processes and methods. The model is called the O-CDIO and it builds on the foundation of an established engineering framework called the CDIO, also presented later in this thesis [7,8,24]. The overarching theme and objective of this reform and the research project was to create engineering education where the 'Engineer Meets Humans' and acknowledges and utilizes the fact that engineers need to understand the user and the needs behind any given problem space, technical or non-technical. In addition, they need to be able to use human-centered methods along with one from the natural sciences in order to achieve these goals. A multidisciplinary science university that teaches all the classical disciplines offered a productive platform for researching potential change in the education of engineers.

In short, to achieve collaboration, it has to be enacted together with students and faculty from other disciplines. The reasoning is that an engineer's working life is and will be multi-, cross-, inter-, and transdisciplinary [6,3,25,26,27]. This can and should be learned already at university and in the context of a multidisciplinary science university that can offer its in-house potential for such study.

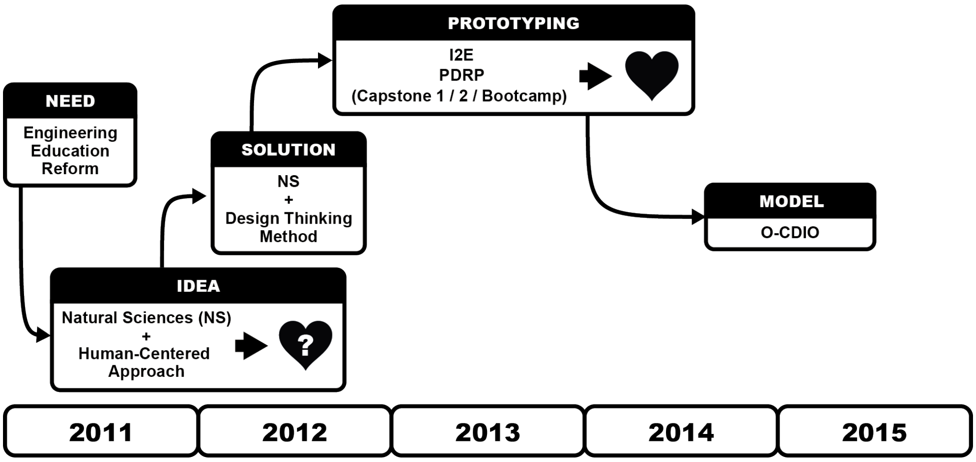

Figure 1. *The process that lead to the creation of the O-CDIO framework. The main aim of the model is to educate engineering students to become* ***problem definers*** *in addition to* **problem solvers**. *The reasoning for this is that it enables them to better answer to the needs of the complex phenomena of current and future engineering challenges. The figure presents the research process. The reform process began in 2011 with the idea of testing whether the strengths of a multidisciplinary university could be utilized for education in engineering by means of the CDIO framework [7,8]. The background research and present-state-analysis, done in Fall 2011 and Spring 2012 gave impetus to the testing of a human-centered approach with design thinking methods in the teaching of engineering, in addition to the natural sciences approach. Courses such as Introduction to Engineering (I2E), Product Development and Rapid Prototyping (PDRP), Capstone and Capstone Bootcamp were piloted during 2012 to 2014 to test these ideas. Please refer to figure 9 (p.48) to see the time line for each publication and to figure 11 (p.54) to see to which research question each Publications answered. To see, which Publication focused on which topic in the research process, please refer to figure 8 (p.53). The results from the piloted courses, together with the literature and the scientific discourse, led to the induction of the O-CDIO model and are presented in section 5, Results II.*

There is still a clear need for very specific and highly disciplinary engineering knowledge and praxis [3,6,16-18,28]. An engineer using natural sciences and systems thinking as the foundation for work has an important role in many businesses, processes, and industries and in the foreseeable future, too [3,6,16-18,28]. Innovations, however, require people and ideas from diverse backgrounds and cross-disciplinary approaches [e.g.29-32]. It can happen in different contexts: student projects in academia, new business ventures and entrepreneurial activities serving yet to be discovered needs, or in finding new ways to manage societal challenges. Innovations need both natural sciences, and methods based on human-centered design thinking for creating the structure, content and shape of innovation [18,19,31,32]. This is also the foundation, and context for the O-CDIO model [Publication VIII].

Research motivation and objectives

This section presents the overall structure of this thesis. The first part of this thesis consists of sections from Introduction (section 1) to Conclusions and Limitations (section 6). In the introduction section the rationale, theme and purpose for the study were presented. Next, the basic facts of the University of Turku (UTU), the engineering education reform process that took place in UTU, and the research context for this study are introduced. Also the research questions and a preview of research methods and research context are presented. Section 2, Background, presents a summary of literature related to engineering education research especially from the perspective of developing engineering education at a university level. Also the development of global engineering education in general is introduced. A summary of the main activating teaching methods is presented to provide the reader some idea of the literature behind the research question 2. Section 3, the research methods and data collection, the epistemology of the study, how the data was collected and examples of analysis methods close to the qualitative analysis method used in this study, are presented. The idea is to provide a preview how, from which target group and when the data was collected and how it was analyzed. Finally two examples of the analysis process are provided. Section 4 presents publications and other results of the study. Section 5 presents the O-CDIO framework that was induced from the results and the literature. Finally in section 6, the conclusions and limitations of the whole study are presented. The second part consists of the articles, later referred to as Publications, attached to this thesis.

The University of Turku (UTU) is the second largest multidisciplinary science university in Finland, and the largest that offers university education in engineering. UTU is a community of approximately 23 000 students, faculty and other staff, and has seven different faculties and seven independent research institutes [33]. UTU was founded in 1920 as an independent university with the slogan “A Free Nation’s Gift to Free Science” – although the roots of the university go back to 1640 when The Academy of Turku was founded. The right to award engineering degrees was granted to UTU in 2004.

Engineering Education is integrated into the faculty of Mathematics and Natural Sciences, which also contains the disciplines of Information Technology (IT), and Biotechnology (Biotech). The degree structure is based on the Bologna model and the BSc degree is three years and 180 credit points (ECTS) and the MSc degree is two years and 120 ECTS [34]. These are divided into three different majors at the Department of Information Technology (IT) and three different majors at the Department of Biotechnology. Regarding the faculty, IT has three professors, thirteen university lecturers and five researchers for engineering [35]. Biotech has four professors, and seven teachers. In addition, Biotech has twenty-eight researchers who do research into both Biotech (MSc TECH) and Master of Science (postgraduate students excluded). The MSc side of IT also has a faculty whom teach and do research for both the science and engineering sides [36].

The IT department has around 550 students in both the BSc and MSc engineering programs. Annual graduation from both the BSc and MSc degrees is a little less than 100. In 2014, for example, 42 BSc and 49 MSc degrees were awarded [37,38]. Biotech has around 100 students. Altogether, the yearly engineering education intake into UTU is approximately 200 students. In 2014, it was 189 students as seen in Table 1 [37,38].

	INFORMATION TECHNOLOGY	BIOTECHNOLOGY
Students	550	95
Students graduated 2014 (both BSc and MSc)	91	13
Researchers	5	28
Lecturers	13	7
Professors	3	4

Table 1. Engineering education in UTU is comprised of IT and Biotech. There are around 650 students. Yearly graduation in both BSc and MSc degrees is approximately 100. There are 20 lecturers and 7 professors [the figures are from 2014, 33,37,38].

The reform process in UTU

The process in UTU started in summer 2011 with the faculty management identifying preliminary needs, and designing the overall objectives and plan of approach to the reform project. The author of this thesis was recruited to manage the reform project from October 2011 onward. Below is an excerpt from Publication I, about the situation at UTU when the reform process was beginning in the summer and fall of 2011.

Engineering education in Turku comprises of Information Technology [IT] and Biotechnology. Especially in IT, there is an on-going development process "Engineer meets Human" where the goal is to integrate the key strengths of the multidisciplinary university into the engineering education. This is done by introducing thematic multidisciplinary profiles from UTU's excellence areas to the curricula of the engineering education. Integration of multidisciplinary thinking and courses into the engineering studies is done in both bachelor as well as in master's level. In UTU the development of engineering education started in June 2011. The change process received positive support from the top management of the university and from the management and faculty of the IT–department. In August-September 2011 it was realized that CDIO might prove as a useful platform and a holistic way of thinking for the development process. The change process towards CDIO structure and constructive alignment in planning and teaching started with the forming of five change teams.
The five teams consisted of 21 different persons from the faculty and student representatives. Five persons from the faculty were in more than one team. [Publication I, p.2-3]

The planning for the change process in UTU engineering started during summer 2011. It actualized during the fall of that year and it is seen to be a continuous process without a defined end date. From fall 2011 to fall 2012, there were five change teams that were responsible for the planning of the reform. The teams were in no particular order: Strategic Thematic Profiles team, IT Core Competencies team, The CDIO team, Working Life Readiness, and the Study Plan team.

Out of these five teams, the Study Plan team continued its work until spring 2013. Figure 2 presents the teams and the members in them. All of the teams had student members in them.

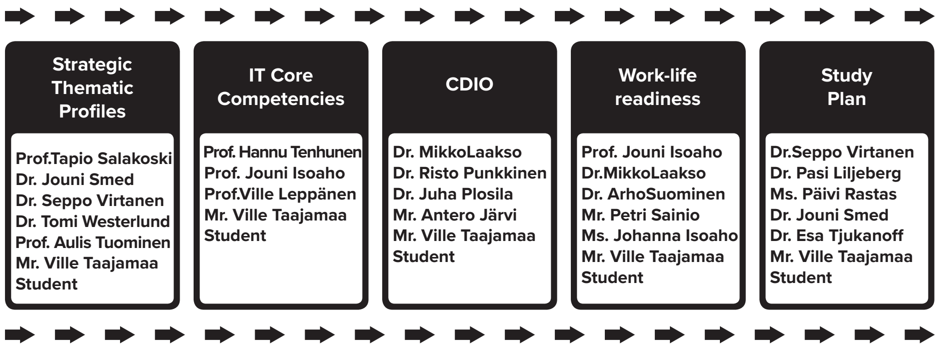

Figure 2. Change teams that were formed to create the action plan for UTU's engineering education reform. The teams started in fall 2011 and continued until fall 2012. The study plan team worked until spring 2013. The goal was to reform

engineering education toward a more hands on and project-based learning approach, and align the curriculum to support interdisciplinary education during the degree studies. The author of this thesis was in all of the teams.

Research Questions

The research project leading to this thesis started from the need to reform the engineering education at UTU. There was no clearly stated research question or research group per se when the reform project started. The author of this thesis started the research project and process as a means to document, analyze, reflect on and develop the plans and interventions that were being implemented as part of the reform process [e.g. 5,39]. From the very beginning, one of the overarching themes for the reform process has been the context of e*ngineering education (EE) in a multidisciplinary science university* and *how EE can be integrated into that setting so that the students receive the maximum benefit in terms of transferable working life skills in addition to the disciplinary knowledge gained from their education*. This process has the working title and slogan: *Engineer Meets Human*, which stands for the idea that engineering students should gain the maximum benefit from working together with students, industry, faculty and other disciplines already during their studies. The rationale being that they will have to be able to do this during their working life. This was also the guiding hypothesis of the reform process, that engineering students would benefit from being exposed to different disciplines. This thought also later translated into research question 1 presented below. In this sense, the main research theme of the research is: *Developing Engineering Education in a Comprehensive or Multidisciplinary Science University.*

This grand theme is approached case by case from the perspective of *transferable working life skills, the curriculum and teaching methods development, and the knowledge base* – widely acknowledged in, for example, engineering education research [e.g. 2,14,16-20,34,40-43]. The piloted courses that were designed and prototyped as part of the research have their individual research questions, which reflect the Intended Learning Outcomes (ILOs) of the courses. *These questions are dealt with case by case in the Results I section and also in Publications I – VIII attached to this thesis*. The pilot courses were designed to prototype EE at UTU, and they have since lead to the inductive inference of the O-CDIO Engineering Education framework, which is presented in the Results II section of this thesis. See Figure 3 for a visual demonstration.

The final research phase was approached from two perspectives that were formulated to research questions (RQ´s) 1 and 2

RQ1: How can the CDIO framework be implemented to a Multidisciplinary Science University, covering the whole of engineering education?

RQ2: What activating teaching methods work best in a setting of international and interdisciplinary engineering education?

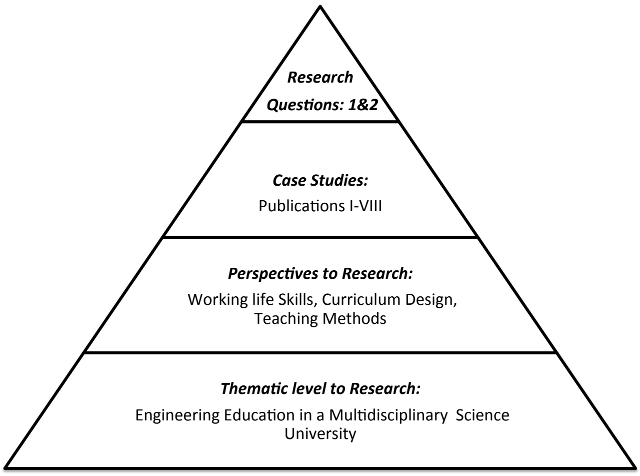

Figure 3. The structure of the research questions. The first level is the thematic level, which provides the context and grand theme for the research. The second level is the perspectives through which the research is conducted, the third level consists of the research questions that were constructed case-by-case depending on the need and the phase of the reform and development process, the last level are the actual RQ´s of this thesis research.

These questions combine both the structural and content approach to the reform process and to the framework that was induced during the research. With a limited number of graduates each year the objective of the engineering education reform was to create added value to the national and international level engineering education. From the very beginning the hypothesis was that by utilizing the different disciplines of the university to the full the engineering students would firstly gain better understanding about what needs other disciplines have and secondly they would understand their own role as engineers better. The question was what teaching methods would then work best to achieve these goals.

Research method and context

This section will give an overview of the research methods and the context of the study. The research methods together with the epistemology of this thesis, a table showing the data collection methods, and examples of the analysis methods are presented in more detail in section 3, the *Research methods and data collection*.

When researching the behavior of human beings there are no absolute laws such as in natural sciences, nor inductive or deductive [44-47]. A mixed methods (MM) approach that is coupled with triangulation, however, adds to the richness and reliability of the results and especially to the conclusions drawn from them [48-50]. This research, and the research in the piloted courses relating to this research, is based on action research, or participatory action research (PAR), and mixed methods including case study analysis, grounded theory method, and quantitative analysis methods [47,51-54]. The fundamental research theme during the reform process, including the piloted prototype courses at both Bachelor and Master's levels, has been developing engineering education in the setting of a typically resourced, classical and comprehensive research university. The research methods included audio-recorded semi-structured interviews with engineering faculty, students, the management of the university, and representatives of industry; in addition, there were observations, surveys, study journals and interviews. The context was the present-state-analysis and the five different pilot courses – which were designed and implemented to prototype the education models for the courses – and are presented in this thesis [11,55,56]. Course surveys, study journals and interviews were based on the intended learning outcomes of the piloted courses and the relevant literature [12,30,31,40,57-61]. The data set used for this research is drawn from 251 different students from 31 faculty members, 3 alumni, and 2 industry representatives. The time line of the research is from fall 2011 to fall 2015. There were more than 11 000 (11 559) data points when all the questions and their answers were calculated together.

The work-in-progress O-CDIO model is derived from the discourse between constant data analysis and the literature review. The interview analysis method and approach followed the reflexive pragmatism method [55,56]. That approach aims to gain valuable results in a pragmatic way by acknowledging that there is an existence of reality beyond both the egocentricity of the researcher and ethnocentricity of the research community [11]. In other words, context matters.

The research project and this thesis is produced through a consistent and conscious approach to viewing the researched phenomena from different angles, instead of approaching it from one point of view, a single set of values and one vocabulary. In one sentence: if it makes sense, it works.

2. Background

In this Background section, we will first introduce the factors leading to and influencing engineering education reforms, the contemporary history and changes in engineering education, and the present state of engineering education [e.g. 4,8,12]. Then the CDIO framework and approach and the design thinking approach are presented first independently and then together. We will also present experiential learning method, often applied in engineering education as it will provide theoretical background to RQ2 [e.g. 62-64].

Engineering Education Reform

Graham (2012) made a thorough international investigation of engineering education reforms, which was documented in the report: *Achieving Excellence in Engineering Education* [14]. The report states that there is an ongoing development towards *experience led engineering education*, which is, in many ways, what UTU was aiming towards as well [e.g. 17,40,65,66]. Most importantly the report asks the question *how* is reform achieved in addition to the questions *what* and *why*. According to the report, engineering education needs to be able to continuously change and develop to meet the needs of global and local society and industry [14].

According to Graham (2012) in most cases the question is not whether there is need for reform or not, a continuous development process is or should be a natural state for any engineering education degree. The world surrounding us is continuously changing as well. The question is: how to achieve it? The challenge of how to make it happen is the un-known factor. According to the report the conditions where systemic change is successfully initiated vary and there are usually one or several factors influencing it [14]. These factors can include for example that there is an identified significant threat to the “market position” of the department or school in questions. It can be, for example, problems with employability or recruitment. It can also be a political situation where there is gossip about political decisions threatening the existence of that particular education model or degree [14]. Often the change is catalyzed by the recruitment of faculty with industry experience and/or newly hired faculty replacing retirees.

In many cases, the leaders of successful change have experienced failure in previous change attempts. They have understood that change must be radical in order to stick [14]. The success of change also correlates with the extent to which the change is embedded into a coherent and interconnected curriculum structure. Failure is often due to an isolated curricular change or over-reliance on just a few faculty members [14]. The department level is seen to be the right level for change. Having a dedicated department head is critical to the success of the change process. This person is typically appointed from inside the department and was very highly regarded in both research and teaching activities. A long-standing trust in the department head amongst the faculty means that the faculty believes that their change efforts are valued and that the reform work will lead to promotions and rewards [14]. There is typically very little dissemination of practices across departmental boundaries. One of the most difficult issues found in the report is the ability to sustain change. There is a natural tendency to return to the *status quo ante,* i.e. to the way things were before. Many change projects suffered difficulties around 5-10 years after the first student cohorts from the new curricula [14].

In order for the change to happen and the development process to be sustained, there are some critical issues, in addition to the abovementioned, that needs to be considered in an educational reform. For example, does it continue even if the there are other restructuring processes in the university happening as well, or if there are changes in the faculty, especially in the senior management? According to Graham (2012) those reform processes that are sustained are those reforms that have a cross-section of faculty involved in the delivery of the reformed courses, and an ongoing focus on educational redesign, reinvention and innovation as well a well-disseminated impact evaluation [14].

The Graham report shows that there is significant effort being put into engineering education (EE) reform all around the world. For “lonely champions” trying to make change happen by themselves the report has no good news. These changes prove to be both short-term and limited in impact. Instead the key to success is widespread faculty engagement with departmental leadership and a process that is coherent, sufficiently ambitious, well-informed and excellently communicated to all stakeholders [14].

Shifts in Engineering Education

To understand the UTU reform process, and the main contribution of this thesis, the O-CDIO framework, this section shares a perspective on the major changes within engineering education during the past 100 years according to Froyd et al., 2012. Figure 4 below shows the five main changes [12,67-69].

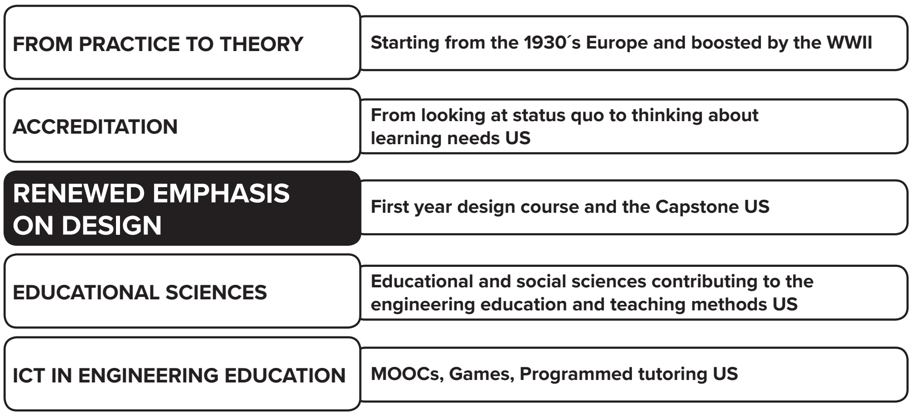

Figure 4. The five phases of engineering education development during the last 100 years. This thesis research focuses on the third phase, which is a renewed emphasis on design.

The engineering science revolution started by shifting its focus from hands-on practice to more mathematical modeling and scientific analyses. This shift was initiated from Europe and the multiple engineering breakthroughs in physics in the early 20th century that accelerated during World War II. Next came the accreditation of the engineering programs. The results of the changes in the accreditation processes are not one-sided. For example, it has to be asked whether accreditation has stimulated or actually slowed down the development of engineering education [12,70]. Second, has science-based EE shifted too much focus from the users to a purely technical approach [41,65,71].

Ongoing changes in engineering education

The next section will present the five major shifts in engineering education one by one but in this section the three shifts that are still ongoing are presented.

The first ongoing shift in engineering education concerns the introduction of design into engineering education. In the thesis, this can particularly be seen in UTU's first year engineering design course and the final year Capstone Project course. Both have received much attention from the engineering educators and researchers around the world [e.g. 22,72,73]. This has been partly influenced by engineering education research, although that did not bring design, a distinctive feature of engineering, to the forefront of engineering education [e.g. 13,17-19].

Another shift is research on engineering education, which has developed and influenced the way learning and teaching occur in engineering education [12,24,47,74-76]. The main contributions have been the focus on the ILOs and the effects on various teaching approaches and theories that are based on social constructivism and cognitive psychology [57,64]. Gaining input from the social sciences has accelerated engineering education research, although there is still discussion as to whether it is better that the research on engineering education is conducted by engineers themselves or researchers from the social sciences [12]. In order to ensure the richness and rigor of the research, this thesis takes the view that both approaches should be included. Ultimately, the key question is whether one's own background – with its hindrances and benefits regarding science – can be recognized and taken into consideration when conducting research in the EE domain. To reduce possible bias and make the research more objective, EE research should be conducted in collaboration with other disciplines. Otherwise the question arises, how is it possible to teach students to learn about interdisciplinary issues if a faculty remains entrenched in its own disciplines?

The third change and wave of development that is still in progress is the role of ICT in engineering education and education in general. In sum, the three ongoing engineering education development processes according to Froyd et al., 2012, are firstly added emphasis on design, secondly engineering education research and its implications for engineering education, and finally the use of information and communication technologies (ICT), such as the Internet, in engineering education [12].

First shift from the 1930s to the 1950s – from hands-on engineering to science

The focus on natural sciences instead of hands-on engineering practice started in Europe in the 1930s. After it became popular at US universities, they started replacing machine shops with courses on mathematics [12]. This phenomenon accelerated during World War II when physicists produced societal changing inventions such as rocket engines and the nuclear bomb [12]. This steered military funding from engineering to the natural sciences and thus what became funded also became researched.

There is an ongoing debate on whether engineering education should be divided into more science-based or more hands-on based approaches [2,6,19]. The idea of having two tracks in engineering education, one that is theoretical and science-based, and one that is hands-on oriented is not new [77]. The Grinter report made for the ASEE, American Society for Engineering Education, in 1955 introduced the idea of two tracks for engineering education [12,78]. The report proposed that one track would focus on the professional and general, while the other would focus on a more scientific approach. Due to the possible funding for the universities mostly coming from the military, the final report only focused on the scientific part. Although the Grinter report focused on science, there was a recommendation to have courses on the humanities as well. The idea was that engineers would then be better equipped to work and interact with people other than engineers. This did not, however, catch on and the core of the first wave, from roughly 1935 until the late 1960s, was that hands-on engineering was more scientific-based [12]. In Europe this teaching emphasis has lasted longer. In some places, an emphasis on theory and science still prevails [34].

Second shift from the 1980s to the early 2000s – accreditation: from teaching to learning

The second wave was about the change in the accreditation system and came about as a result of the development of engineering programs. Before the 1990s, The Accreditation Board for Engineering and Technology (ABET), mainly took care of and reflected the status quo of engineering education. Nevertheless, development started in the 1980s and early 1990s and was led by the University of Michigan and Massachusetts Institute of Technology (MIT). This resulted in a radical change in the accreditation process of engineering education. The pragmatic outcome was the EC2000 (Engineering Criteria 2000) constructed by ABET. This is also when the CDIO model began to form [7,8]. The main element in the new thinking was that it changed the approach from a teaching-based assessment to a learning outcomes assessment. In other words, it went from looking at what we teach to examining what students should learn. This change has had a clear impact on engineering education as the ILOs for the degrees and courses in engineering education have become a standard practice [79].

Third shift early from the 1990s to the present – a renewed focus on design

Third wave of change included a renewed emphasis on design [86]. One of the main reasons for this was that the natural sciences had taken up so much room on the degree structure, that engineering students did not even know what design meant [2,17-19,12]. Design in this context stands for a broad amount of definitions. It is a set of methods and practices relating to the lifecycle of an engineering process that has a beginning, implementation phase and an end. Adding design teaching to UTU's engineering curriculum has enabled both faculties and students to learn design skills during a four-year engineering degree [41,65]. One of the difficulties, though, is the myriad of definitions related to the word "design". Definitions range from natural science systems thinking and design based on actual machine, mechanical or other technology to human-centered design skills, which vary from holistic design thinking processes, such as the needfinding, storytelling, and prototyping skills, to areas like business thinking [80-82]. The latter typically occur in a team project environments. For further reading see Publication III and Publication VIII of this thesis.

Capstone design course as part of the design experience

The most significant shift in the design wave has been the introduction of capstone courses into the curricula of engineering education [42,83]. One of the pioneering real-life, open-ended capstone project courses is the "Design Clinic" course at the Harvey Mudd College in California, US. This course dates back to the mid-1960s [e.g. 17-19]. Capstone is a very broad definition for a course that combines material and learning from previous years within a design-based project. This means that the content, setting and structure of a capstone experience varies a lot [12,17-19]. A capstone course can mean writing an essay independently and individually during one quarter in a high school [14]. Or it can be a year-long MSc level interdisciplinary project-based course in a team setting and with a very open-ended real-life challenge [20,21].

The majority of capstone courses in an engineering context aim to bring the practical side of design and engineering to the curriculum. The goal is to introduce the learning outcomes that are thought important for working in industry.

Howe 2010 has listed the assessment methods of capstones, including several different methods and practices, such as individual deliverables throughout the term, group deliverables throughout the term, final group deliverables, and also evaluations by other team members [83]. For further reading see, for example, Publication III and Publication VI.

Another practical embodiment of design practices within an engineering curriculum is the first-year engineering experience, often called the *Introduction to Engineering*, *Cornerstone* course, or *Freshmen Design* course [12]. This started in the 1970s and 1980s and it has been shown to have a positive influence on student development and retention [39]. The I2E courses and their influence and results are successfully and widely reported in engineering education research domain [e.g. 6,8,16,19,84]. The reasoning for conducting an I2E course is to lead education towards a problem-, project-, and team-based approach already during a student's freshmen year. Thus, the prognosis for the whole study time is more aligned with the expected outcome concerning transferable working life skills [Publication VIII, p.5]. For further reading see Publication II and VIII.

The second and third year of engineering education have stayed very much the same for the last few decades, which has created a gap in their design experiences. The process of linking theory to practice should happen in a constant and continuous flow. This need to integrate the experience of design between the first and the last year has been recognized but there has been very little action taken to induce change [17,18]. One of the main characteristics of the O-CDIO engineering education framework, presented in *Results II* section of this thesis, is to ensure that there is a constant and continuous exposure to design courses throughout the curriculum – from day one to the final capstone course at MSc level. For further reading see Publication VIII.

Research in engineering education, especially research based on educational sciences has played a role in bringing new theories and methods to engineering education [57,85,86]. Behavioral, cognitive and social psychology as well as the social constructivist approach to learning are the main disciplines and epistemological approaches in the field [87-91]. Although the extent of the adoption of the pedagogic theories and especially their implementation into daily practices varies, educational sciences have influenced both the curriculum design and the learning methods [8,43,70]. According to Froyd et al. 2012, the intended learning outcomes for students have become the *modus operandi* for engineering education and for the ABET requirements [12]. For example, curriculum design and learning methods include approaches such as aligned curriculum active learning, storytelling-based learning, and problem-based learning. The majority of structures and learning methods are based on the social constructivist approach [e.g. 57,66,92].

Fifth major shift – ICT in education and in engineering education

The future role of information and communication technologies (ICT) in education was predicted already during the late 1950s. [12,67]. So far, the main channels that have been developed for ICT usage in education include areas such as content delivery via the Internet, individualized student feedback through programmed instruction, intelligent tutors: the second phase of individualized student feedback, personal response systems, computational technologies, simulations, games and competitions, automated grading, and remote laboratories [6, p.1352].

The rapid development of Massive Open Online Courses (MOOCs) has mostly put courses online – but only in addition to teaching them onsite. The Internet has provided a channel, a means for distribution, and brought about a significant change in the distribution of educational material, however, the pedagogics have stayed very much the same.

Current state of engineering education

After looking into what kinds of changes EE has undergone in the last 100 years, we will now take a look at the present state of engineering education [4].
According to Cheville 2012, the current state of engineering can be seen from five different perspectives id est from the policy, technology, the society, program level and finally from the student perspective [4].

The question concerns which stakeholder group the observer belongs to. For an educational developer and an educator, the main focus concerning education starts with the student, or at least it should. Other aspects either serve this need, or provide an environment for it to happen [4].
Cheville 2012 presents four interlinking themes: the *philosophical basis* for engineering, the *role of experience*, *resources* and finally the *change* that occurs in the process. These themes explain and connect the aforementioned five perspectives [4].

Engineering education is a complex and an adaptive system that interacts with all the stakeholders: policymakers, practitioners, administrators, representatives from industry, and students. Getting this system to operate in harmony is a demanding task, to say the least. Cheville 2012, aptly shares the metaphor of the tale of Sisyphus, comparing him to an educational developer. Sisyphus was sentenced by the Greek gods to roll a stone up a hill, only to fail to reach the top before the day was out. This illustrates the task of an engineering education practitioner quite well [4]. Even if you are able to serve one master, say, the student, some of the other stakeholders might be displeased with that situation. The interlinking themes provided by Cheville focus mainly on three perspectives: society, program and, most importantly, the student.

The CDIO Framework

Before going to the context of engineering education, its background, history and future, a short introduction to the CDIO framework is presented because the model of this research project is built on the CDIO framework [7,8]. Also, it is the framework and model for engineering education that was implemented by UTU during the reform process [e.g. Publication I].

The CDIO approach

The CDIO framework aims to educate students who, after their graduation, are "ready to engineer" [7,8]. This is achieved by educating students to an engineering lifecycle where students understand how to *Conceive-Design-Implement-Operate* engineering processes, and engineer products and processes that add value. This is most often enacted in a team-based environment [8,24].
The three fundamental and underlying premises or fundamental ideas that the CDIO approach has are firstly that underlying needs are best met by making the engineering education context reflect the CDIO cycle of operating processes, systems and products, secondly that the planning of the learning outcomes should be made together with the relevant stakeholders and there should be a sequence of integrated learning activities, which exposes the students to a situation similar to those they will face in their profession, and finally that integrated learning activities mean that students learn both personal and interpersonal skills at the same time as they learn the engineering fundamentals [9].

The O-CDIO engineering education model, which is the main result of this thesis, builds on the CDIO model and shares all of the underlying premises with the CDIO model. The added value or difference in approach is that the aim in the O-CDIO model is to create holistic, radical and disruptive innovations instead of incremental or solely engineering-based solutions. This is achieved by combining interdisciplinary skills and design thinking together with other human-centered methods of engineering education [e.g. 20,21]. Both models aim for integrated learning outcomes and both utilize, for example, experiential learning methods [e.g. 57,64]. In the O-CDIO model the emphasis is on the early phases of the engineering lifecycle, emphasizing a human-centered perspective in addition to the systems, product and process approaches. This human-centered approach means using methods such as needfinding, storytelling, and human-centered prototyping in addition to systems thinking and natural sciences-based problem-solving [e.g.28]. In essence this is a ´yes-and´ perspective where the CDIO focuses on ´engineers who can engineer´ and the O-CDIO model focuses on engineers who can ´engineer and innovate´.

The vision and goals of the CDIO approach

The vision of the CDIO approach is to stress the fundamentals of engineering education in the context of the Conceive-Design-Implement-Operate process [8]. The key features of this vision are firstly that engineering education is based on clear student learning outcomes, program goals, and active stakeholder involvement. A curriculum should also be aligned and have both disciplinary courses and courses that develop personal and interpersonal skills in the context of the CDIO engineering lifecycle. There has to be a steady exposure to Design and Implement (C-Design-Implement-O) experiences set in an engineering-based experiential learning context. The learning approach must be based an active and experiential learning, which in turn must be incorporated into lecture-based courses and finally there must be a systemic and comprehensive assessment and evaluation process [8, p.15]. The goals of the CDIO approach are to prepare the students so that they master both disciplinary knowledge and larger entities [8]. For example a student should master a solid working knowledge of technical fundamentals, be able to take leadership roles in the creation and operation of new engineering products, processes, and systems, and understand and appreciate the impact that research and technological development has on society [8].

In addition to the goal setting, the definitions of the approach and the epistemological stance on engineering education, the CDIO approach contains a model syllabus, learning outcomes, examples and advice on integrated curriculum design, advice on teaching and learning, and on how to assess learning and evaluate the program. In addition, there is an active CDIO community and the CDIO approach can be seen as one of the great successes in the advancement of global engineering education [7,8,9,24]. For further reading, see section Results II in this thesis.

Design thinking

In the scope of this study and the O-CDIO framework, design thinking is defined as an approach that has a specific intention. Whether it is better design, better business or a better quality of life it is always with a goal or, as suggested earlier, with an intention. This definition differentiates design thinking from many other approaches or sciences that often serve a clear cause but not by definition. Philosophy for example aims to increase the understanding of life and the wisdom of knowing, and it has a right to exist without any clear or practical aim or purpose. Philosophy exists for the sake of philosophy. Design thinking in this research context, as well as in the engineering education context, exists to serve a need – always and without exception. Design thinking and especially design thinking methods are often related to new product development and radical innovations [30,93]. Design thinking is seen as a way of thinking that can significantly enhance the design process and its outcomes [31,32,81]. Design has many definitions but most authors agree that design thinking is a way of solving problems that require purposeful thinking, as well as thinking while working with others, which will lead to new outcomes [30-32].

Design thinking as an approach

According to T. Kelley and D. Kelley 2013, design thinking is a process consisting of four stages; inspiration, synthesis, ideation and experimentation and Implementation [32,80]. Studies have shown that in addition to actions, design thinking is a combination of practices and cognitive approaches as well as a mindset [80]. Design thinking methods and processes are used for solving difficult, complex and loosely formulated, open-ended problems. There is rarely, if ever, one correct answer to a problem [59]. This calls for a holistic approach if one wants to produce systemic and holistic solutions [32,59,94].

Traditional university teaching based on the transmission of disciplinary information and ways of searching for solutions are often based on natural science or methods too linear to be able to solve complex real-life situations [95]. Students need to acquire thinking and working skills to cope with and excel in solving complex or wicked problems, but their education often leaves them ill-equipped to do so [6,17,18]. In Publication III design thinking is defined as follows:

> *Depending on the source there are many ways of describing the characteristics of the cognitive process, which is in the core of design thinking. Some describe it as abductive [19,26], some integrative [16,18] or divergent balanced by convergent thinking [16,18]. All these emphasize the importance of creating multiple new solutions to choose from instead of choosing from existing alternatives or creating only one solution to a problem [16,19,18]. Thus, the explorative content of design thinking emerges already on a cognitive level [9]. Mindset and attitude towards problem solving and practices also play an important role in design thinking. It can be described as explorational and experimentational activity [22] that has a continual character [16,22] to it. One of the most important tools for experimenting and searching for solutions is prototyping [18] in various ways and from early on. One aspect that surfaces in various sources is user-centricity [e.g. 22,23,27] and therefore testing one's ideas and prototypes with users can be stated to be of importance as well. The outcome of experimenting and going through rounds of trial and error should be learning and identifying directions for the process - that might not have been taken otherwise – while aiming for a significantly new solution to a problem by questioning what is already known [22]. Therefore, the nature of solving open-ended problems requires disregarding the fear of failure [24], acceptance of ambiguity [15,27] as well as the ability to reflect in action [11]. [Adopted from Publication III, p.3]*

Design thinking mindset

The Rainforest model, created by Wang and Horowitt 2012, presents two sets of rules: first the rules for innovation and second the rules for production [96]. The rules of production and staying in the safe zone are presented on the right of Table 2, and they apply to the conservative approach. Production can be seen as a linear model for engineering education as well. But for innovation to foster a different set of rules (the left column), different approaches need to be implemented. The rainforest rules are close to the design thinking approach and mindset [20].

	RULES FOR INNOVATION		RULES FOR PRODUCTION
1.	Break rules and dream	1.	Excel at your job
2.	Open doors and listen	2.	Be loyal to your team
3.	Trust and be trusted	3.	Work with those you can depend on
4.	Seek fairness, not advantage	4.	Seek a competitive edge
5.	Experiment and iterate together	5.	Do the job right the first time
6.	Err, fail, and persist	6.	Strive for perfection
7.	Pay it forward	7.	Return favors

Table 2. The Table above presents the rules of innovation versus the rules of production. Both sets of rules are de facto correct. It is context dependent as to which approach is more suitable [96]. The thinking can be extrapolated to engineering education as well. If the goal is to focus on incremental product development or production, the set of approaches can be designed more conservatively than if the goal is to achieve radical innovations.

The rainforest approach also presents the underlying theme and approach that the O-CDIO engineering education model has. The aim is not so much to fine tune the well-established CDIO model but to aim for radical innovations through the use of human-centered methods, and to focus on the early phases of the product development and project management lifecycle. This has implications for how engineers should perceive their role during their studies and at the workplace. Not to mention whether the engineering educators see themselves as educators with the privilege of fostering growth or as scientists forced to teach. This topic is more thoroughly discussed in the Limitations and Discussion section of this thesis.

The roles of prototyping

One of the pragmatic manifestations of design thinking approach, and the O-CDIO frameworks, is the focus on prototyping. Erickson 1995 has found three different audiences for the prototype [97]. These audiences include the supporting organizations and the team doing the actual design of the product and, most importantly, the user. All of these stakeholders or audiences have different roles and needs. For the organization the idea is to show how the project is progressing. The design teams can come up with new ideas and directions from the existing prototypes, give feedback on how to improve the existing one and also find new ideas for the actual product. Users can come with valuable feedback on usability, desirability, viability and feasibility [97]. The communication of the idea and purpose of the prototype is important, especially the perspective on what it is being built for. Building a prototype that addresses all three audiences: organization, design team and the actual user is challenging. Each audience will typically have several questions that the prototype should be able to clarify. However, one should not use too much effort, resources or energy in the building of one prototype, otherwise the actual time and other resource costs will become too high [97].

Kim discovered that different disciplines are required when designing complex systems [25]. Nevertheless, people from different disciplines have different vocabularies and different values, thus the term prototyping might have different meanings within a team. Different people call different things prototypes. A designer or artist will call a styrofoam model a prototype. A programmer will call a front-end webpage or a test program a prototype and business people or user-designers will call a storyboard scenario of some situation a prototype. All are prototypes. Which meaning is used and where and when is dependent on the situation: who is the customer, what is the status of the project, and what is the final goal and the intended achievements [25].

According to Share (1996), organizations also have different kinds of prototyping cultures. This means that some prototypes are valid while others are not. The single biggest factor affecting this is: *how is the prototype used?* As a result, the determining factor is not how it is made, but for what for and how is it to be used [98].

An important issue with prototyping, which applies to all creative or ambiguous situations, is that the team making it must have complementary skills to be able to approach the task from different angles and with different prototyping cultures and methods [23]. When looking at the terminology in prototyping there are two main words: *resolution* and *fidelity*. Resolution refers to how detailed the prototype is and fidelity refers to how close it is to the actual and desired final design [23]. Houde and Hill 1997 define a *Designer* as anyone who designs and creates the prototype, whatever their job title might be [23].

Look and feel, implementation and *role* are the three dimensions of the prototype and each have different aspects and questions that need to be answered. ´Look and feel´ refers to how the user experiences the whole ´using experience´, i.e. how it feels to touch and use it, how it looks, how it makes a person feel. ´Implementation´ includes all the technical issues the prototype has and how it actually works on a detailed level. ´Role´ answers the simple and important questions: What kind of role will this prototype play in the user's life? What purpose does it serve? What unique quality does it offer the user? Asking the right questions, whether it is concerned with appearance, functionality or user-friendliness is crucial when deciding what kind of prototype to build [23].

Prototyping process

Houde and Hill (1997) list the important factors concerning the prototyping process as firstly an ability to define the prototype broadly. A prototype should answer the most important design questions in the least amount of time. The simplest prototype can be the most effective in its representation [23]. An engineer should also be able to build multiple prototypes. Be prepared to throw several prototypes away if needed. Building a prototype is an art itself [23].
Knowing the audience to whom the prototype is being built is also important. A prototype should always be built to its audience. Too many features or too fancy looks can even harm the design process or at least guide the users' decisions [23]. This also includes the dimension that certain design questions can be communicated by certain kinds of prototype. A designer must also be ready to explain the prototype to the audience. Prototypes do not necessarily do this automatically [23].

Prototypes are built to test hypotheses and ideas. By clearly defining what the prototype actually represents, to whom it is being prototyped and why, better decisions can be made on what kind of prototype should be built. As there is an emphasis on accelerating the speed of learning, the prototypes need to be low resolution and leave as much space as possible for new ideas. They need to focus on just testing the idea in question. They can be *communication prototypes*, which merely present just one idea. Or they can be *lookalike prototypes* that give a physical idea of the product, or they can be *critical functional prototypes*, providing *technical proof of concept*. The prototype should be easy and affordable to build. If it is too ready, it can inhibit development by limiting the possible solution space and the flow of new ideas. Hence, in the early phase, the emphasis should be on tangible 3D prototypes. This will allow for the creation of new alternatives and ideas [23].

To summarize, using prototypes in a process of rapid iterations, hence testing ideas and finding and spanning the boundaries of a solution can enhance learning profoundly [20]. This is why it is one of the key factors and a key ILO in the PDRP course as well. The aim is to minimize the barriers to learning.

CDIO and Design thinking – mapping the O-CDIO framework

Combining design thinking and the CDIO framework is not a new thing. There are relevant experiments and reported experiences from both Polytechnic and research or Science university levels [e.g. 99-101]. In addition there are several recognized institutions that use very similar approaches though they are not labelled as combinations of CDIO and design thinking, see figure 5 [e.g. 103,104]. Although most of the research concerning CDIO and design thinking together are either course or degree level, the problem setting is very much the same as in the UTU reform and the emerged O-CDIO framework. Especially in Singapore there are two different cases where design thinking is explicitly embedded into the CDIO engineering curriculum at different stages of education [99,100,105]. First in a polytechnic, which uses design thinking approaches both in freshmen and later in senior capstone-courses at a program level and secondly a research university that combines design methods throughout the whole University´s curriculum [101,105]. Sharing many similarities both in the goal setting and in the implementation these approaches also differ significantly from the O-CDIO framework. In the first example it is already the very status of the higher education institution, which in this case is a Polytechnic that focuses on education, instead of education and research. The goals of implementing design thinking to the CDIO framework are the same but the challenge setting is very different. Another difference is that in the reported cases it is done at a single programme level, not at university level. So not only the allocations between teaching and research are different but it also focuses on three single courses at BSc level and not at all to MSc level. In the research or Science university case the newly established university is not a comprehensive Science university, and the program in question is being consulted and partly managed by a distinguished American university, namely the Massachusetts Institute of Technology, MIT [101,106,107]. According to the published articles, however, the adoption of methods, designing of curricula and faculty development are designed and implemented together [e.g 106,107]. With all the differences considered, however, the results from the reported studies are well aligned with the findings in this thesis. Especially the freshmen experiences as well as the capstone findings resonate with the findings in the Publications II and III.

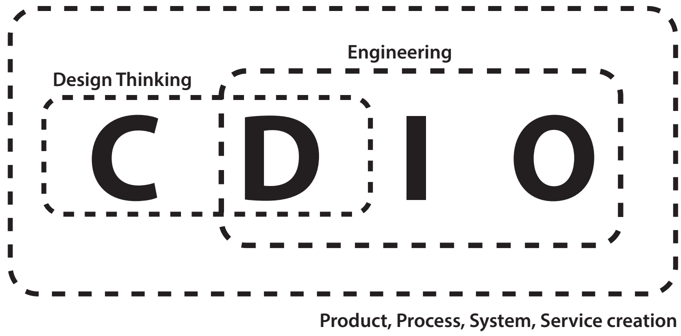

Figure 5. The role of CDIO and Design thinking in Capstone courses by Fai 2011 [figure based on 100]. The core idea of implementing Design thinking methods to the engineering process cycle is very much the same as in O-CDIO. The differences are in the scale and context meaning course or programme level versus university level and also polytechnic versus a science university.

As mentioned above relevant examples can be found much closer to home than Singapore. Aalto University Design Factory (ADF) is an internationally recognized example how human-centered approaches and methods can be implemented to the engineering curriculum [104]. ADF operates both as a platform for students, researchers, entrepreneurs and industry representatives to work together as well as a platform for capstone courses. Please see Publication IV for further reading. Still the O-CDIO framework does differ also from this case in a clear way as it is university level approach and although operates in a same national context it differs clearly in the university context. Aalto University is a combination of three main disciplines: Engineering, Arts and Business, as UTU is a multidisciplinary university with all the classical disciplines. In addition to ADF also the d.school in Stanford University, California US has a similar approach to combining design thinking and engineering [20,102]. Many of the same differences between ADF and O-CDIO apply to d.school as well. In addition it operates in a different national culture.

All of the cases presented above resonate with the O-CDIO in many ways. The mindset, many of the approaches and methods and the overall goals have several shared surface boundaries. The education reform done in a Nordic multidisciplinary research university, in an in-house manner is, however, a unique and complementing case to the abovementioned. The O-CDIO framework and the use of design thinking methods in an engineering curriculum can be defined as adding another case in a unique context to this broader practice and scientific discourse. In other words, though adding design thinking to engineering education has long roots, starting at least from the 1960´s in the US, the context of Nordic multidisciplinary science university adds another dimension to the discussion of practice based engineering education development [e.g. 4,14,17].

Learning methods in engineering education

Engineering graduates need a broad palette of working life skills in addition to disciplinary knowledge to help them tackle complex real-life challenges and problems [2,17-20]. In addition, future engineers also need thinking skills that can help them solve problems that cannot be solved with rational and straightforward problem-solving methods or systems thinking that is based on the natural sciences. The teaching methods that are used play an important role in both *what* and especially *how* the students learn. And, in addition, an assessment as part of the teaching method defines what the students will focus their attention on because 'you get what you measure'. This section deals with different learning methods in the context of engineering education. Essentially very little has changed since Confucius and Socrates introduced their learning approaches [108,109]. However, it is relevant to skim through the main ideas and teaching methods that are related to engineering education.

Cooperative and inquiry-based learning

Cooperative learning has social interdependence theory as the underlying assumption behind it [92]. Research into it shows that using cooperative learning typically results in 1) higher achievement and greater productivity, 2) more supportive and caring relationships, and to 3) greater social competence [12,92].
When practiced in the context of engineering education, inquiry-based learning methods typically start with a challenge or a prompt that needs to be addressed [16,18,88, Publication III]. The openness and wickedness of this challenge can vary considerably [20]. Project-based learning, problem-based learning, and challenge-based learning are practical approaches to the challenge- and inquiry-based approach. These approaches enrich the engineering curricula and methods but do not solely solve all the challenges connected with educating engineers. There should be a balance of belief in the methods and flexibility – and in how they are used so that the tail does not wag the dog. This applies to other learning

philosophies as well. For example, Bandura's social learning theory as well as the theory of perceived self-efficacy have greatly influenced design thinking methodology [30-32,85].

Experiential Learning

John Dewey presented the idea of learning through experience in his books *Experience and Education* and *How to Think* written in the early 20th century [62,63]. These books are regarded as the bases for the experiential learning approach, which at that time represented, and surprisingly, in many cases, still does represent, the progressive school of thought on education. Learning by doing and hands-on learning are derived from this approach and represent a school of thought in which the key words are: experiment, purposeful learning, experiment, individuality and freedom [63].

Experiential learning is fundamentally different from the learning approaches that are offered by the behavioral sciences, which represent the idea that education is something of a static nature, representing a fixed body of information that can be transmitted to a student through an organ called the teacher [62,63]. Dewey, however, did not see traditional school and progressive school as opposing each other but as contributing to each other.

Experiential Learning Theory (ELT) is based on six propositions [64].

1. Learning is a process. Students need to be engaged in a process that has a continuous feedback loop.
2. All learning is relearning. The beliefs and ideas that a student has must be tested and examined so that they can be refined into new ideas, which are built on existing ideas and beliefs.
3. Disagreement, conflict and differences drive the learning experience. The learner must move back and forth between reflection and action – feeling and thinking.
4. Learning is not an isolated process. Learning includes adaption to the whole world. A learner is a holistic person who feels, thinks, reflects, behaves and perceives.
5. Learning is a process of assimilating and accommodating new experiences and thoughts into existing structures and concepts, and vice versa.
6. ELT is based on the constructivist theory of learning, which opposes the ´transmission´ perspective of learning where ready-made ideas, which are static and fixed are transmitted to the student, who obediently accepts the information without processing it. In constructivist and

social constructivist learning theory, knowledge is created in a social process and the knowledge created for the individual is his personal knowledge and is based on his prior concepts and structures of knowledge [57,86].

List 1. The six ELT propositions [62-64,86].

In ELT knowledge is created through the transformation of experience [64]. This is a holistic approach and the transformation experience includes cognitive, affective as well as psycho-motoric approaches to learning. This is something that for example many of the learning taxonomies do not take into consideration [110-111].

ELT has two dimensions to learning that interact continuously with each other. The first is the *exposure to experience*, which goes from *Concrete Experience (CE)* to *Abstract Conceptualization (AC).* The second concerns how the *experience transforms* during that journey from *Reflective Observation (RO)* to *Active Experimentation (AE)* [64]. Experiential learning is a process where all this takes place in a continuous learning cycle that consists of all the processes related to learning: reflecting, thinking, experiencing and acting [64].

3 Research methods and data collection

The goal of scientific inquiry is to acquire truthful knowledge about the object of the inquiry [112, p127]. Scientific methods are used to make the inquiry process rational and systematic. In addition to the truth goal pragmatic goals such as added explanatory power can contribute to process of adding knowledge [112]. This is also the rationale for the use of institutionalized and theoretically approved methods in this thesis. This section is divided into three main parts. In the first part, the research categorization is presented based on the taxonomy of research methods by Järvinen 2004, plesase see Figure 6 [113]. In section 3.1 the epistemology and the philosophical worldview of this study is presented. In section 3.2 an overview of the qualitative and quantitative research methods are presented together with the mixed methods approach. Section 3.3 will focus on how the research and analysis methods were applied and how the data was collected in this study.

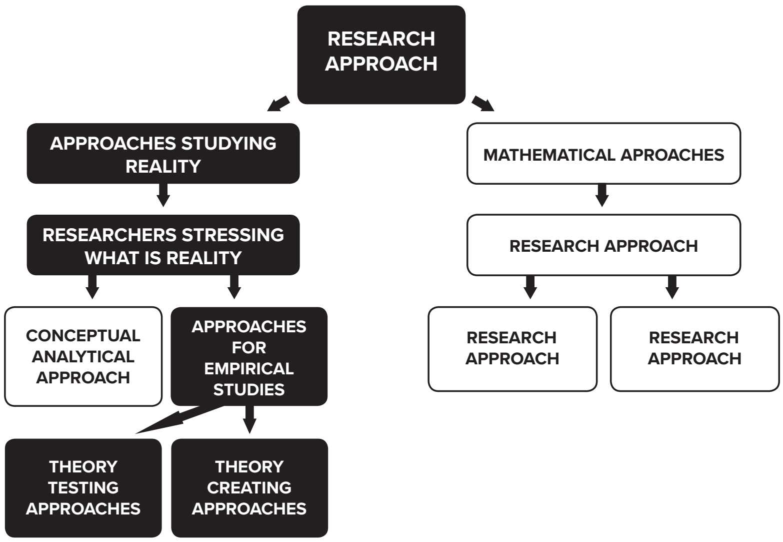

Figure 6. The research method approach according to Järvinen 2004 [113]. The research methods of this study are aligned with Järvinen´s taxonomy of research

methods originally developed to Information Systems [Figure re-designed from 113]. This thesis research followed the black track with the objective of both theory testing and theory creation.

The main approach was qualitative while quantitative methods supported the analysis of research findings. Järvinen´s 2004 taxonomy, which focuses on both research questions and research objects, provides the frame for the research approach. Research approach is defined by Järvinen 2004 as a set of research methods that can be applied to the similar research objects and research questions [113]. Later, in section 3.2, the participatory action research (PAR) method, grounded theory method (GTM) together with the case study analysis method are presented with examples from the research cases [44,51-53]. These constituted the closest established methods of analysis in comparison to the qualitative analysis process in this study. Reflexive pragmatism gave the epistemological background to the interviews and influenced the perspective taken in the analysis of the interviews [56]. This approach is explained in section 3.2 section as well. Reasoning is that the recorded audio interviews were one of the main data collection methods. After introducing the methods and approaches two examples of the analysis process is given to shed light on the different phases, methods, and time frame of the analysis. There were altogether 11 559 data points collected during the research. The number of data points comes from when all the questions from different cases are multiplied by the amount of answers given. One data point can be a single tick in a box in a survey feedback or it can be a text document that contains transcribed text worth tens of minutes of talk from a recorded semi-structured audio interview. Internal and external limitations of the research methods together with challenges of inductive reasoning and the reliability, and transparency of the whole research are presented in Section 6 the *Conclusions and Limitations*.

Epistemology and the philosophical worldview of this thesis

The Philosophical Worldview, also referred to as *epistemology, paradigm* or *ontology* can often remain hidden in research [114]. We either see no reason to elaborate on it, or the researcher may not come to think of it while conducting research and reporting it. Whether the epistemology of the research is hidden or reported, it influences the practice of research and should always be stated, followed and reported [114].

The majority of engineering educators, and many of the engineering education developers, have their educational, and professional backgrounds in the natural sciences [14,59]. In addition, especially at university level, engineering educators tend to have their disciplinary expertise and research embedded in the natural sciences. This means that they focus on quantitative methods with a positivistic worldview in their research. Undoubtedly, this is an advantage when developing disciplinary content, research and expertise in the technical or engineering context. This research's foundation is, however, on a human-centered approach, with a human-centered worldview, and it uses human-centered research methods [e.g. 114-116].

This research is based on both the pragmatic approach as well as the social constructivist research approach. Method-wise the pragmatic approach is more prevalent, since it offers adequate levels of freedom in the choice of research and analysis tools – including the Mixed Methods (MM) approach with quantitative methods for analysis and theory testing. The use of MM with quantitative data analysis has been proven to add value to this research project. For example, during the analysis phase of this research, the quantitative analysis revealed results that could have been misinterpreted or interpreted in other ways due to researcher bias [46]. Quantitative research has provided a useful foundation by elaborating on the quantitative results and giving space for the research and analysis of the ´qualities´ of the phenomena [46]. Social constructivist theory, on the other hand, is the predominant philosophy of research in the sense that it focuses on the researched object, in this case the student providing the theory of learning. This research follows the pragmatist school of thought, especially concerning the research process and used research and analysis methods [114]. It borrows a lot from constructivist and social constructivist epistemology as well. The three aforementioned epistemologies co-exist well and are close to each other. A clear distinction can, however, be seen between the positivist, and even postpositivist worldviews [114]. To summarize, this study is based on the social constructivist theory of learning and behavior, and it utilizes the pragmatic approach [46,47,52].

The Social Constructivist Worldview

The constructivist and social constructivist view is typically associated with qualitative research and it aims to add to the understanding of the world that we live in. In research, typically qualitative, an inductive instead of deductive approach is preferred in order to add to our understanding of the complexities of human life. Social constructivism aims to generate a theory inductively instead of testing one. It starts from the assumption that humans interact with other human beings and with the world in order to make sense of it and find meaning [46]. This means that both meaning and knowledge is contextual and cultural, and although it is always individual it is constructed in a social process. Meaning is always an interpretation of something, and it´s made by humans [46]. In other words, there is no one single truth ´out there´. In social constructivist worldview doing qualitative research, researchers interpret the findings they have collected themselves. Interpretation is influenced by the researcher's own culture, background, and experiences [46]. Methods wise this means that the analysis and the generation of qualitative theories are inductive and go from specific to general and typically, in social interaction, with the research and researched community. This especially applies to Participatory Action Research (PAR), which is used in this thesis [46].

The Pragmatic Worldview

The pragmatic worldview focuses on real-world research problems. Instead of selecting a method or a theory, the starting point for a research situation is identifying the problem that needs to be solved. In this thesis study the case was an identified need to reform engineering education at university level.

Once the problem is identified the researcher representing the pragmatic school of thought will select the research and analysis tools applicable to that specific problem. Typically, the toolkit is pluralistic, containing several methods, approaches and tools of analysis that are selected with a very clear metric: if it works – it is the right tool. Perhaps because of this straightforward approach pragmatism is often brought up and discussed as a method more than a philosophy or as a worldview to research [115]. This does not do pragmatism justice. Mixed methods and mixed methods research (MMR), which is used in this thesis, is often interconnected with the pragmatic approach and pragmatism as a paradigm. This connection is also helpful when getting past the main caveat of pragmatic worldview, which is its reduction to only a practical approach [115,116]. The pragmatic approach is especially applicable in MMR, as it poses no boundaries to the methods used, whether quantitative or qualitative. This means that any method, procedure or technique is permitted if it proves helpful in solving the identified research problem and truth is defined as what works for the research problem [115]. The researcher looks for *what* and *how*. The question of *why* is not of much relevance. That said, a pragmatic researcher agrees and acknowledges that research inevitably takes place in a context driven world where culture, history, and social interaction influence the research and researcher. In brief, the pragmatic approach enables the use of mixed and multiple methods, as well as the use of different data collection and tools of analysis. If it works for the specific problem at hand, it is the right method [114-116].

Overview of the main methods and approaches

Qualitative and quantitative research methods share similarities in how the research process is conducted. However, the philosophical assumptions, strategies of inquiry, methods used for data collection, analysis, and interpretation differ [46,114]. In essence, the praxis and structure of the processes share similarities but the content and methods are different [46,117,118].

This research is based on qualitative research although quantitative methods are also used. The mixed methods palette includes the actual research setting: action research, which is based on a qualitative approach and data collection, inquiry, and methods of analysis from various different approaches: open-ended semi-structured interviews (qualitative), surveys (quantitative + qualitative), observations (qualitative), frequency analysis (quantitative), the Wilcoxon signed rank-test, Bonferroni correction, Kendall's tau analysis methods (quantitative), case studies, grounded theory method and reflexive pragmatism (qualitative), and both inductive reasoning and deductive analysis (qualitative + quantitative) [119-122]. Qualitative methods in both inquiry, and analysis have a clear emphasis, although quantitative methods have brought variance and contrast to the research project.

There are several caveats regarding the use of qualitative research methods. Partly because of this and mainly because it was pragmatic, this thesis research utilized mixed methods in order to achieve more transparency and reliability in the research and in the analysis phases of the results. Quantitative methods provided numerical support for the research, which added to the richness of the phase of analysis [119].

Using mixed methods that combine both qualitative and quantitative approaches led to more pragmatic, goal-oriented and in-depth results. Quantitative results tell us *what* is happening, and qualitative results add to our understanding on *why* that something is happening. In this research, the *how* has resulted in a new model of engineering education namely the O-CDIO model. In this section we skim through the main quantitative research methods used in this thesis. As stated earlier, quantitative methods have had a supporting role in all of the research project. Frequency analysis, and different tests have, however, proven helpful – especially in the course feedback assessments and analysis where the researcher (author) has also been the developer and main teacher in addition to being the principal investigator. For this thesis, frequency analyses, correlation analysis and Wilcoxon and Kendall's tau rankings with Bonferroni corrections have been used. A short description of the quantitative methods that were used in this thesis is presented next.

A frequency distribution will show, usually in graphical form, how many times each ranking occurs. This is one of the simpler quantitative analysis methods and it is very useful for obtaining an overall picture of the researched phenomena and assessing their properties and how the rankings are distributed [119].

A Wilcoxon rank-sum test is a non-parametric test used to evaluate whether two samples differ from each other [119,120]. It was used in this study to analyze the I2E, and PDRP course surveys in order to find questions that received answers which were significantly different from the average. Kendall's tau is a non-parametric correlation measure [119,121], used to examine the course survey data for the I2E and PDRP course correlations in order to find out whether certain answers correlated with the final rankings received for the course. Bonferroni correction was used to adjust the required p-values, correcting for the multiple hypothesis testing that uses both the Wilcoxon rank-sum test and Kendall's tau [123]. For further reading see [122, Publication VIII, p.5-6] and [114,119-123].

Participatory Action Research

The overarching research conducted in this thesis is based on PAR [46,87, 116,124]. Giving a definitive and comprehensive definition of action research is difficult. The usage of the term, practices, and methods may vary depending on place, setting and time [104,125]. Educational and social scientists such as John Dewey and Kurt Lewin were the early adopters and users of action research [116]. What is common to most of the conventional action research settings, however, is that they start with a situational research setting and with the aim of making an intervention in that situation – in addition to identifying a research problem, gathering data on it and analyzing it. In short, PAR includes real-world intervention and ´action´ in order to solve the problem identified [87]. Action research may include many cycles and loops of problem identification, data gathering, analysis, action phase, gathering data from the intervention, analysis of the intervention, design and identification of next steps, and then if needed, the whole cycle again [87].

In collaborative action research the researcher acts and influences the social world that is being researched [124,125]. Intervention occurs through critical inquiry with the participants in the data set. This can also be labelled critical ethnography [126,127]. See Figure 7 for further detail.

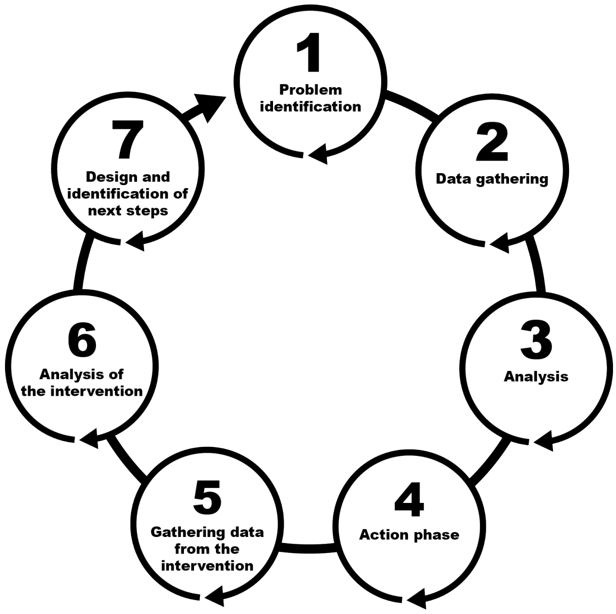

Figure 7. The Action Research or the Participatory Action Research (PAR) loop. In the UTU reform process, and in researching it, many different research approaches, and methods were used and they fit under many umbrellas. Please see also figures 8 & 9 for further details concerning the research loops of this thesis research.

In this thesis the overarching research method was PAR because the author was also involved in the reform process as well as in course ideation, teaching, research, and development. In PAR one important element of the approach is that it includes intervention in the phenomena being researched. The loop described in Figure 5. happens several times during a PAR process. In this research there were seven PAR loops from fall 2011 to fall 2015 as described below. The approach within the PAR loops was pragmatic as the selection of the tools and methods varied according to the phenomenon being studied [46,126,127].

Grounded Theory Method

A method similar to the grounded theory approach and method (GTM), was used in this thesis as the main tool of qualitative analysis (see next section *The research specific data collection and analysis methods* for more details). More precisely grounded theory method defined by Strauss and Corbin, not Glaser [44,52]. The rationale is that Strauss and Corbin allow more interplay between the data and the researcher than the Glaserian approach. Glaser argues that there can be no interaction and interpretation between data and the researcher [44,52,128]. Although the GTM method was similar to the actual data analysis method in this thesis, this study is, however, based on pragmatic and social constructivist epistemology. Both of these worldviews see no ´absoluteness´ in either data gathering or the analysis phase of the research.

Definitions in GTM:

Methodology: a way of thinking about and studying social reality

Methods: a set of procedures and techniques for gathering and analyzing data

Coding: the analytical processes through which data are fractured, conceptualized, and integrated to form a theory [52, p.3-5].

Grounded Theory Method offers a way of thinking and viewing the social world. It is also a set of procedures and techniques, as well as a combination of methods [129,130]. In using GTM the researcher also uses his own experiences. This will help make comparisons, and discover properties and dimensions. To deny the interplay between data and the researcher is to deny humanity itself. Theory is grounded in the data and it is validated through concepts used during the research process. This is the way conclusions can be achieved. Flexibility and openness means that there has to be room for ambiguity. Social phenomena are often complex and difficult to fathom. Premature closure in the avoidance of ambiguity or uncertainty does not serve the process of analysis.

Underlying the grounded method is the need to do actual field research and discover what is occurring in the subject's world, to determine the relevance of the emerging theory that is grounded in the data and develop the discipline as a basis for social action, to examine the complexity and variability of phenomena and human action, to apply the belief that people become actors when they take on an active role in responding to problematic situations, to realize that persons act on the basis of meaning, to understand that meaning is defined and redefined through interaction, to be sensitivity to the evolving and unfolding nature of events (processes), and to develop an awareness of the interrelationships among conditions (structure), action (process), and consequences. [52, p.7-12].

Qualitative research can also be defined as non-quantitative, if it does not use any statistical procedures. Qualitative methods in GTM can include observations and interviews, and these are part of qualitative research but from a method's perspective, and they quantify qualitative data. Grounded theory analysis method is, however, a non-mathematical process of interpretation in order, first, to discover concepts and relationships in raw data, and second, to organize the discoveries into a theoretical model or scheme. Data for the analysis can include qualitative methods, such as interviews and observations and, for example, documents, films, and even data that have been employed for a different purpose.

The main reason for choosing GTM and qualitative research and the analysis approach in general is that it serves the needs of the process related to the EE reform in UTU. In this case, finding underlying themes from the data in order to find a basis for a holistic concept and a model that would set engineering education on a sustainable, practical, feasible and viable path [131,132].

Case study research

Case study analysis method is another example of a well-established analysis method very close to the qualitative analysis method used in research. The main feature of building theory from case studies is continues and frequent overlap with the analysis and data collection phase. According to Glaser & Strauss (1967) theory building, which is a central activity in organizational research, should be based on empirical reality that permits the finding of a relevant and valid theory that can also be tested [44]. There is, however, vivid discussion when to use which theory-building method and how (see for example Ketokivi 2010), what are the strengths and weaknesses at which case, when and how to combine them and how to evaluate them [51,55, 56].

Case studies typically combine different data gathering methods such as literature review, archives, interviews, questionnaires and observations. The data, empirical evidence, may be qualitative such as words or quantitative meaning numbers or a combination of these [53]. Case studies start how majority of research methods and methodologies, which is by constructing the setting for the research. If possible the prevailing and previous constructs are good to acknowledge as this might add the richness of the gathered data and to how the emergent theories can be identified, analysed and evaluated [51,53]. A case can include both quantitative and qualitative material. It can also be either qualitative or quantitative. Quantitative data can support the findings form the qualitative analysis though it can also keep the researcher from being mesmerized by the impressions from the qualitative data. On the other hand qualitative data can directly point to a specific phenomena that then can be quantitatively tested [51].

Data analysis is the very core process of building a theory from case studies. It is also the most mystified and un-codified. Research methods and data collection are often vividly described but the analysis process is given very little room.
Generally it is considered that the more explicit and well documented the process is the better and more validity the analysis has. One of the main challenges in the analysis phase is the amount of data that should be analysed. And it does not help that when looked in enough detail there eventually is as many approaches as there are researchers [51].

Finally tentative themes, relationships, maybe even correlations between variables begin to emerge. Shaping hypothesis is a highly iterative process where the researcher constantly compares theory to data and vice versa. The fit between data and theory is one of the cornerstones of building a theory through case research [51,53]. Literature review phase is an important phase in reflecting the emerged theory to the existing theories. Questions such as what similarities and differences can be found and why. Finding contradicting literature is important. It forces the research out of the comfort zone and from making easy decisions [51,53].

Case study research can create new insights from juxtaposition of paradoxical and contradictory data. Juxtaposition activates the researcher to think out-of-the-box. Secondly a case study is potentially testable and thirdly the results are very likely empirically valid. The weaknesses side are that usually there is a vast amount of data and it is impossible to try to capture everything. This shouldn´t stop the researcher from aiming to do so [51,53].

Reflexive pragmatism

Interview situations are a complex and ambiguous blend of social, psychological, political and individual knowledge-expressing situations affecting several discursive processes. Also local context, space, the energy level of the interviewee and interviewer, the time of the day, the themes selected and many other small yet relevant issues always influence the interview situation. They are not overwhelming, however, and abstractions can still be made. Self-interest and local specificity are not the only influencing factors. Instead of having only political or other social intentions, an interviewee can have a genuine willingness to serve science and aim to share knowledge as openly and objectively as possible. Of course, the above-mentioned prerequisites concerning the interview situation need to be taken into account when analyzing the data. Local context, political motives, language barriers and the powers of language have to be recognized when constructing social reality in the interview situation. This especially applies to the analysis phase [11,56].

In reflexive pragmatism the focus is on the actual interview situation and the interviewee. Reflexivity in this context stands for a consistent and a conscious approach to viewing the researched phenomena from different angles instead of approaching it from one point of view and a set of values and vocabularies. Reflexive pragmatism in interviews takes into account the tensions between logics such as the communication of facts and experiences, political action, script following and impression management. It challenges what the data are all about. Instead of working with just one theory, reflexivity empowers the researcher to find several meanings in the data – depending on the approach. Social and linguistic complexities should also be acknowledged, understood and used to elaborate on the complexity of the discourse that takes place in an interview situation as well as in the analysis phase [56].

Using the reflexive approach, approach used in this thesis, has two potential advantages. First, there is no ungrounded belief that the ´data´ could reveal an undisputed reality or a single ´truth´. Second, a reflexive approach gives an opportunity to value the complexity of the empirical material. This provides a chance to explore more than just one set of meanings. Also, by accepting ambiguity in the explored phenomena the reflexive practitioner can be more creative. Pragmatism means that there has to be a balance between the sense of direction of the research, radical skepticism, and endless reflexivity. Ultimately, results and their pragmatic interestingness, usefulness and credibility are the determinants. The key point is that as long as it adds to the discussion it has value. This way, the most pragmatic, valuable, interesting and strongest point of view can be found. Pragmatism in *reflexive pragmatism* stands for the fact that resources, such as the time, space and patience of different stakeholders, are limited. Pragmatism also means that the end goal is to achieve and deliver results. Transparency and validity is achieved when these results are assessed with adequate self-criticism and the transparent and well-documented presentation of the methodology used [11,56].

To focus on quantity when collecting empirical data can lead to the wrong kind of robustness. Not all the interviewees can have the same impression or participate in the same discourse. Quantity alone is not adequate because the researcher is part of the social world that is being studied. This emphasizes the need for exploration, and self-examination. The research will inevitably produce results that are embedded in the power and discourse of the very same frameworks that are being studied. Hence, it is important to have a pragmatic approach with an emphasis on relevance and pragmatism in contrary to overdriven rigor. The risk is that the researcher's personal experience comes to dominate or even attempts to produce explanative accounts of his own position, preconceptions and interests. This amplifies the importance of the MM approach and the benefits that quantitative methods bring to the analytical process [46,123,133].

The research specific data collection and analysis methods

The main methods for data gathering in different cases in this thesis study included semi-structured interviews and feedback surveys either on paper or through a web link. Secondary data was obtained through observing and the use of other material such as project reports, annual reports, and exams from the courses, prototypes from the courses, study journals, and course presentations. Secondary data amount is not calculated to the cumulative data amount presented in last section (11 559 data points). For the semi-structured audio interviews 31 faculty members, 41 students, 3 alumni and 2 industry representatives were interviewed during the whole research process. The interviews lasted from 30 minutes up to 120 minutes but were typically between 45 and 60 minutes. All of the interviews were audio recorded and the majority of them were done in a setting of two persons: the researcher and the interviewed person. Only two interviews were done in a group setting where there were 16 students present in both interviews [Publication VI]. All of the interview questions were designed in a team setting lead by the author. The interviews were all audio recorded, later transcribed to text documents and then analyzed using an iterative and explorative analysis method following the principles of GTM and the case study analysis, presented earlier. Secondary data was obtained mainly through participating to the researched phenomena, by examining different documents or by observing the researched phenomena. In practice this could mean auditing a course that was utilizing the methods being researched, as was the case in Publication VII for example. Or by examining the produced reports, study journals and by observing the learning process in addition to gathering primary data, as were the case in Publications III, VI and VIII for example.

The data gathering in the reform process in UTU engineering as well as the development of the courses preceding the O-CDIO model utilized semi-structured interviews as the main research method [117,133,134]. A total of 31 faculty members, 41 students, 3 alumni and 2 industry representatives were interviewed during this research. The interviews lasted from 30 minutes up to 120 minutes but more typically between 45 and 60 minutes. The goal was to obtain more in-depth data and a participatory view of both the reform process and the outcome of the developed and piloted courses.

In addition to the semi-structured interviews – with the faculty in fall 2011 and spring 2012, and with students in spring 2012, spring 2013, fall 2013, and summer 2014 – the interviewing-method was utilized as part of the development of the pilot courses during the course. This provided beneficial content and ideas onsite, which could then be used to steer the development of the courses while they were ongoing. Using the interview tool in addition to other qualitative and quantitative research methods fits well under the umbrella of PAR and the epistemologies of pragmatism and social constructivism [46,114].
Below the overall research loop is presented in Figure 8. Each of the loops above included loops similar to the loops presented in Figure 7. Figure 9 presents each publications timeline, data collection method, target group and analysis method.

1. Loop 1. The initial semi-structured interview phase aimed at faculty leadership, faculty, students and industry representatives. The goal was to identify what the development needs are in relation to engineering education at UTU, and what action and steps should to be taken in order to make the required development happen. The results of this study are presented in Publication I.

2. Loop 2. Ideating, designing, and running the first round of the I2E course. This was aimed at first year BSc students, and had the additional purpose of acquiring both student and faculty feedback from the course. The results of this course are presented in Publication II.

3. Loop 3. Designing and implementing the first capstone courses for MSc level students – implemented in collaboration with real-world stakeholders. The results of these courses are presented in Publication III.

4. Loop 4. The results of the revised I2E course, which was designed according to the experiences from the first I2E course. The results are presented in Publication II.

5. Loop 5. Designing and implementing the Product Development and Rapid Prototyping course, which was designed according to the feedback and lessons learned from both the I2E courses and capstone courses. The results from this course are presented in Publication VIII.

6. Loop 6. Designing and implementing the Capstone Bootcamp course, the design of which was influenced by both loop 3 and 5. The results are presented in Publication VI.

7. Loop 7. Producing a synthesis of the results. This process lead to the creation of the O-CDIO engineering education framework that builds on the established CDIO engineering education framework [8,9]. This phase consists of elements from all the previous loops. The results of this phase are presented in Publication VIII.

List 2. The seven research loops of this thesis research.

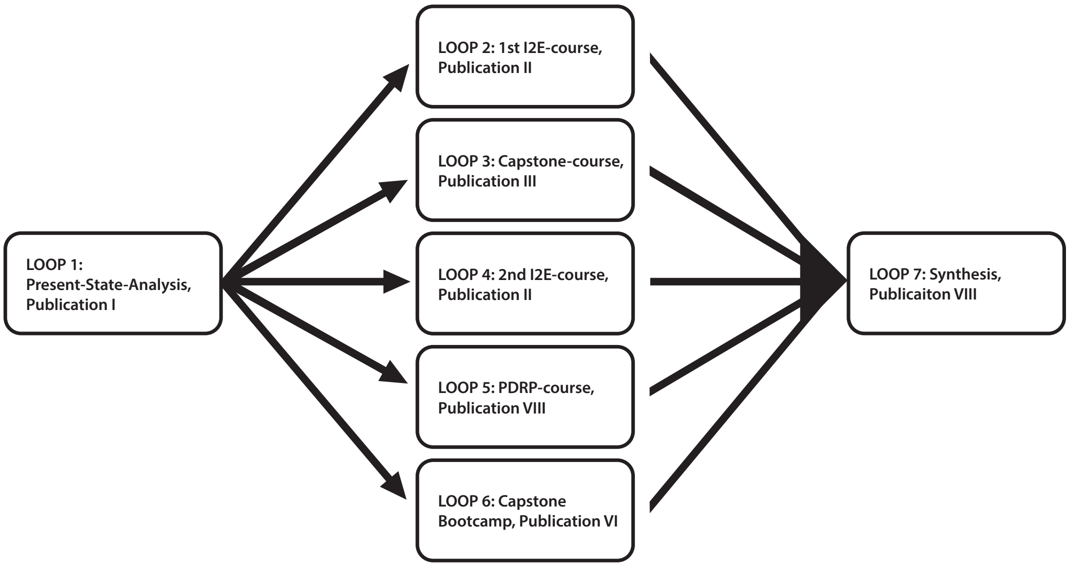

Figure 8. The publications and research loops this thesis research presented in relation to the research questions RQ1 and RQ2. The Loop 1 was a present-state-analysis where the aim was to understand in what conditions the CDIO framework could be implemented to a multidisciplinary science university. This was also answering the RQ1. The Loops 2 to 6 consisted of pilots for both Bachelor and Master´s level courses and different teaching methods thus answering the RQ2. Finally Loop 7 was the synthesis phase, which was influenced from the previous phases.

DATA COLLECTION

PUBLICATION	TIMELINE	DATA COLLECTION METHOD	TARGET GROUP	ANALYSIS METHOD
PUBLICATION I	2011-2012	RECORDED AUDIO INTERVIEWS	FACULTY, STUDENTS, INDUSTRY	QUALITATIVE ANALYSIS (GTM, CASE STUDY, REFLEXIVE PRAGMTISM)
PUBLICATION II	2012-2013	QUANTITATIVE & QUALITATIVE FEEDBACK SURVEY (WEBLINK)	COURSE STUDENTS	QUALITATIVE ANALYSIS & STATISTICAL ANALYSIS
PUBLICATION III	2013	INTERVIEWS, STUDY JOURNALS, QUANTITATIVE & QUALITATIVE FEEDBACK SURVEY	COURSE STUDENTS + AALTO STUDENT	QUALITATIVE ANALYSIS
PUBLICATION IV	2013-2014	RECORDED AUDIO INTERVIEWS	COURSE STUDENTS	QUALITATIVE ANALYSIS (GTM, CASE STUDY)
PUBLICATION V	2014-2015	STUDY JOURNALS, COURSE MATERIAL, OBSERVATION	COURSE STUDENTS	QUALITATIVE ANALYSIS
PUBLICATION VI	2013-2015	INTERVIEW, COURSE MATERIAL, OBSERVATION	COURSE STUDENTS	QUALITATIVE ANALYSIS & STATISTICAL ANALYSIS
PUBLICATION VII	2014-2015	STUDY JOURNALS, OBSERVATION, COURSE MATERIAL	COURSE STUDENTS	QUALITATIVE ANALYSIS
PUBLICATION VIII	2015-2016	INTERVIEWS, STUDY JOURNALS, QUANTITATIVE & QUALITATIVE FEEDBACK SURVEY	COURSE STUDENTS	QUALITATIVE ANALYSIS & STATISTICAL ANALYSIS

Figure 9. The data collection of this study presented with each publication, timeline when the data was collected, the collection method, target group from whom the data was collected, and the analysis method.

Publications I, III and VI were the main publications to utilize an analysis process close to GTM or the case study analysis [51,53,55]. The first case in the reform process that was analyzed with a GTM –based method was the present-state-analysis of the UTU engineering education. After the recorded and semi-structured audio interviews were transcribed, the analysis started by analyzing the interviews in a paper form, underlining words that either appeared often or were otherwise interesting for example were possible outliers. There was no a priori theory that was used to frame the data. The process was not emergent either, as it was in the context of education and university development and the questions were divided in themes already at the interview phase (background, course structure and curriculum, collaboration inside and outside the university, teaching methods). So it can be argued that the themes of the interview already steered the answers to a certain direction, although the content in itself was not affected and it was explicitly emphasized that the interviewee can change focus if so wished. Time wise this the first coding phase took more than two weeks. After that, words that appeared to have similar meaning were clustered together, such as *lack of resources*, *classroom teaching, industry collaboration*. These clusters were formed under themes or they formed concepts already from the clustered words. One example of the latter, being for example the *industry* *collaboration* that rose clearly as a single word or definition from the raw text and was already a theme that could be reported as a finding. A more complex area was for example the *teaching* and *learning* words that appeared in contexts such as *teaching methods*, *learning spaces, disciplinary excellence, learning ways,* and *student motivation*. The concepts and themes were then grouped into a bullet list, or a summary of conclusions, which is presented in section Results I and partly in Publication I. During Spring 2012 the results were also communicated to the faculty and to faculty management. Below are two tables, presented as examples of the structure of the coding process in UTU engineering education present-state-analysis.

CATEGORY	SUBCATEGORY
Learning needs	**Learning, teaching, knowledge, skills**
- Disciplinary knowledge will be outdated in less than 5 years - Scientific thinking is an important skill - Foundation needs to build from several disciplines - Need for more practice based learning (lab work)	
Teaching in practice	**Teaching methods, lecture-based, practical constraints**
- Lecture based teaching - Less and less of resources, no budget or time for new initiatives - Methods should vary on course - No connection to working life skills such as communication - Need for more outcomes based course planning	
Professional development	**Motivation, structure systems, time management**
- Experience teaches how to lecture right - Pedagogic training could be valuable - Motivation should come within faculty - Teaching is not valued	

Table 3. Coding scheme for Teaching and learning in UTU M.Sc. (TECH) education, (sentences translated from Finnish to English by the author)

CATEGORY	SUBCATEGORY
Industry collaboration	**Industry collaboration**
- More courses (hands-on) with industry assignments - More working life orientated approach to support studying- - No feedback from industry - Industry is seen as a static - No-one knows the industry needs in the future	
Department collaboration	**Department level, university level**
- Competition of resource inside the faculty (competition of the resources) - Multidisciplinary university's potentials are not utilized - Limited communication and interaction skills among the staff/teachers	
University collaboration	**Potentials, Competition**
- Multidisciplinary university's potentials are not utilized - Initiatives exists but are not systemic - Having only one major subject would guarantee better students - Competition inside the faculty (competition of the resources)	

Table 4. Coding scheme Collaboration within and outside the department, (sentences translated from Finnish to English by the author)

The second example of concerning the analysis process is from the research that is partly published in the Publication VIII in this thesis. It is the analysis of the qualitative and quantitative feedback data and secondly the analysis of the produced course material such as presentations and study journals of the PDRP course pilot implemented in UTU Spring 2013. The analysis started very similarly as the present-state-analysis and the analyzed data from the qualitative part of the feedback were clustered under themes such as: *Background, Project, Development, Feedback- Teacher, and CourseDev (meaning course development).* These themes were analyzed separately and the words were calculated in them (presented below in tables 5 and 6). Finally all the themes were summarized into table 7, presented below, that was also published in Publication VIII.

BACKGROUND QUESTIONS CONCERNING THE WHOLE COURSE

QUESTION	CODE	QUESTION	CODE	QUESTION	CODE
what inspired me the most		**what was surprising**		**most learning came from**	
we got to do something tangible/start with and idea and end up with a physical object. Since i started in the university	H	i was surprised on emphasis on interactivity of the lectures/ our silence was challenged		interactive lectures / team meetings	
we made programs run on laptop screen - this time I really got to create something					
good visitig lectures		how pd process can be ambiguos	PD	lecture and own conclusions	L/S
positive and supportive lecturer	E			guest lecture	
variety of exercises	H	high quality of finished prototypes	PROTO/PD	most learning as a team / teacher provided with tools	L
practical course instead of theory based	H	teaching style was a positive surprise and effective	CLASS	from all sources: guest lectures, practical work in class and group meetings	L/TEAM
dynamic project teams				interactive teaching enhanzed learning	
practical teaching concept/ real tasks	H	how ideas transmit from class to business	CLASS/PD	lecture / study journals/tasks	L/S
whole picture of prototyping				group work	TEAM
prototyping/hands on expirement	H	high quality of guest lectureres	CLASS	prototyping lecture/team work	L/TEAM
teamwork-possibility to work with other people	TH	the course was more practice oriented than expected	HANDS	from guest lecturer/lecturer - they were really excited about their topic	L
hands on prototyping - getting something to the market		surprising structure/method/goal of course (positive)	CLASS	team members /guest lecture (pdp)	L/TEAM
overall view (small peek) what is needed/included	H				
working with people I hadn´t worked with before	TH	i thought it was going to be a lecture course with exam!	CLASS	working with the group	TEAM
getting to do hands on work /process cycle	H	lack of "project management"	CLASS	group meetings (95%)	TEAM
teamwork/pd process	TH	team work dynamics and flow	TEAM	finding things out for ourselves	TEAM/S
seeing the final projects		shortage of time for doing the project	TIME	team work / lectures	L/TEAM
seeing how much can be accomplished in 5 weeks		biggest surprise is the end result in given time frame	PD PROCESS		
prototyping and working in teams	H/T	working in teams and the hands on nature	TEAM	lectures and hands on sessions and the team	L/TEAM
		i expected traditional lectures but got more	CLASS		
prototyping lecture with Lady Gaga	H	quick and dirty prototypes are so useful	PROTO/PD	working with the team / prototyping lecture	L/TEAM
doing experiment instead of listening to lectures	H	what was accomplished in such a tight time frame	PD / TEAM	from within the team	TEAM
hands on approach /versatility of projects	H	how much people can do with ducktape in 10 min (lady G)	PROTO/PD/CLASS	team fellows	TEAM
hands on approach/ tasks like lady gaga	H	the (high) quality of products being produced including ours	PD/PROTO	guest lectures/ team members	L/TEAM
hands on approach and ideas from other team	H	good quality of lectures	CLASS	from lectures. My team was lazy. This was disappointing	L
Freedom to invent and implement	H	i thought i was prepared for most catastrophes. I wasn´t.		self-studying. Lecture topics reinforced my earlier knowledge	S
the group project		group worked so efficiently	TEAM	doing practical work/intervactive lectures	L
not one single boring moment! Energetic course	E	music/mechanical engineering (pd/manufacturing) perspective	PD / CLASS	lectures / team work	L/TEAM
learning by doing	TH	i was expecting more talking heads / lack of exam	CLASS	from coach and mentors / study journals gave "eureka" moments	L/S
activating people to interact	E			prototyping lecture was good (lady gaga)	
team work / creating something not yet developed	T/H	how complex the product development process is	PD	team fellows/lecturer had a major role in mentoring	L/TEAM
fresh, positive and encouraging atmosphere	E	the project was actually fun!	PD/CLASS	facing problems and lack of ideas and then learning about them in the lecture	L/TEAM
broad view of designing a product		how similar the final presentations were		ideas and inspiration from lectures/ main learning from teams	TEAM/L
hands on work /applying lecture theory	H	course was different from expected from the name	CLASS	lectures and team work	L/TEAM
acquiring proj manag skills		actual hands on lectures and goals - no traditional lectures	CLASS	50% my own / 25% from lecture and 25 % from team	L/TEAM/S
by the doing in the course	H	how much work the course demanded	PD	doing the prototype and prodcut	TEAM
		guest lecturers	CLASS	it was rewarding to see the other team excel	
Summary		**Summary**		**Summary**	
HANDS ON/LEARNING BY DOING	29/40	CLASS /STRUCTURE AND METHODS	18/40	ONLY TEAMWORK	5/40
TEAM WORK	9/40	PD PROCESS	17/40	LECTURES & SELFSTUDYING	11/40
INSPIRING ATMOSPHERE	4/40	TEAMWORK	9/40	LECTURES AND TEAMWORK	19/40
		PROTOTYPING	8/40		

Table 5. The coding scheme for the PDRP-course feedback concerning the whole course.

THE ACTUAL PROJECT

QUESTION	CODE	QUESTION	CODE	QUESTION	CODE
1 things i found positive and rewarding		**2 things and tasks where i excelled**		**3 other positive things**	
interesting and beneficial subject		time management		overcoming thyself	
good team work	TEAM	in my roles inside the team: research/costs	TEAM	class presentations - helped to motivate and improve	
good team work	TEAM	good content and presentation	PRES	good communication and spirit in team	TEAM
great team	TEAM	good presentation	PRES	prototyping lecture was great	
receive appreciation from different people		communication/development/task management	COMM/TEAM		
found a solution/product to lessen human error		supporting other ideas			
developing a real product	PD	contribution to the report	TEAM / RE-PORT	working with different kind of people	TEAM
seeing the real connection between class and real life	PD	willingness to contribute/excelling with the prototype	PROTOTYPE	possibility to work with my discipline (electronic)	
met new people / learned new technologies	PD/TEAM	my part of the project / front end web software	TEAM	the excitment in the class about the projects (all the students)	
good team work	TEAM	organizing the team / business side	TEAM	freedom of doing/creating	
i thought i knew a lot about team work but still I learned				studyjournals helped to track advancement and gather thougts	
great product idea		team work/team communication	TEAM	using english as a communication language	
completing the project	PD				
team work / working with unkown people	TEAM	listening and taking into account other people´s ideas	TEAM	enthusiastic team	TEAM
working with the team /prototype	TEAM	agile project/building the prototype	PROTOTYPE	none	
finding feasible idea		functional prototype/good presentation/ design	PROTOTYPE	really good team	TEAM
team work	TEAM	i got confidence in hardware/software	TECHNOLOGY	none	
other team members motivation	TEAM/WE	we managed to get results in meetings	TEAM	"unorthodox" teaching methods -> gathering information from total strangers	LECT
learning about health care industry		everyone had courage to bring different ideas taken seriously			
teamwork	TEAM	finding the final product idea and agreeing on it	TEAM/IDE-ATION	last lecture with teacher - group feedback	LECT
our team	TEAM	i did a good work with the video	PRES	we were all native finnish speakers	
our team video was great	TEAM/WE				
team cooperation	WE	building prototype/finding ideas	PROTOTYPE/ IDEATION	getting feedback from potential users	
creating our presentation	OUR	visual side of documentation	PRES	we did everything together	TEAM
team work	TEAM	design brief		i did some background research - that helped	
teamwork/rewarding to get something done	TEAM	good role division and communication	TEAM	none	
number of iterations&how much i learned during the project	PD	documentations during the meetings (roles)	TEAM	hands on approach /meeting documentation	
actually finishing a product (that was viable)	PD	keeping the team together	TEAM	collaborating with international students	TEAM
I have a deeper understanding about prototyping now(i got it from the project)	PD	leadership and presentation of idea and product	TEAM/PRES	help from the lecturer and guest lecturers helped a lot	LECT
the end result of the project	PD	the implementation of the project		communication in english/foreign students	
inspiring and couraging atmosphere/ action of doing	PD	background research (my role)		getting feedback from the team and other students	TEAM
seeing the whole process from idea to a ready prototype					
team and team spirit/ also the spirit at the lectures	TEAM	i had the courage to take the challence of being an active member	TEAM	tight time frame made me work intensively	
we made a usable product that looks great	WE	sharing ideas with the team/understanding the process of	TEAM	inspiration from lectures / getting motivation from teams great mood	LECT
i am glad we finished the project	WE/PD	designing final documentation	REPORT/PRES	seeing motivated teams with great products	TEAM
feasible product idea/enjoyed working with the idea i truly believed in	PD	electronics and communicating the idea of the product	IDEATION	excitment helped to geth things going	LECT
scheduled team work	TEAM	communication /our product idea	TEAM/IDE-ATION	encouragement and appraisal from the lecturer	LECT
start something and being able to finish it	PD	embedded engineering (my role)	TECH	great project manager	TEAM
team work	TEAM				
team work in an unfamiliar team	TEAM	delivering on time/fair workload in team/ close to eart project	TEAM	good flow in team	TEAM
from trial error to "trial and succeed" attitude was very rewardig	PD	from sketch to construction	PROTOTYPE	discussion about needed materials and skills	LECT
we got the job completed	PD	our presentation	PRES	team motivated	TEAM
we were able to formulate an idea in to a product idea/presentation	PD	filtering the idea in to a plan/presenting it	PRES / IDE-ATION	prototyping and design lectures	LECT
create a product and get end-user feedback for it	PD	meeting the expected time lines	PROJMAN	lectures for prototyping and design	LECT
seeing th eactual product in our hands	PD	finding the right components for the prototype	PROTOTYPE	use of proj management tools	
seeing the prototype picture	PD	being the project manager	TEAM	good spirit / only healthy arguments	
Summary		**Summary**		**Summary**	
TEAM WORK	18/40	TEAM WORK	18/40	LECTURES	9/40
MENTIONING "we" or "our"	6/40	PROTOTYPE	6/40	TEAM	11/40
PD PROCESS CYCLE FROM IDEA TO PRODCTS	17/40	PRESENTATION	18/40	LECT+TEAM	19/40

Table 6. The coding scheme for the PDRP-course feedback concerning the course project.

These coding themes lead to the summary table (see Table 7), which is also presented below and in Publication VIII.

WHAT INSPIRED YOU DURING THE COURSE?	
Learning by doing / hands on approach	72,5%
Teamwork	22,4%
Enthusiastic atmosphere during lectures	10,0%

MY FEEDBACK TO THE RESPONSIBLE TEACHER	
POSITIVE	
Inspiring teaching style	70,0%
Teaching methods	67,5%
Structure of the course	27,5%
NEGATIVE	
Better admin (webpage, communication etc)	40,0%
Workload too heavy	37,5%
Structure should be improved (workload & time)	25,0%

TASKS THAT YOU HAD PROBLEMS WITH	
Technology	20,0%
Time management	10,0%
Communication	7,5%
Ideation	7,5%
Presentation	7,5%
No problems at all	17,5%
Other	15,0%

THINGS I FOUND POSITIVE AND REWARDING DURING THE COURSE	
Teamwork	45,0%
Doing something with "we" or "our"	15,0%
PD process from Idea to Prototype	42,5%

THINGS AND TASKS WHERE I EXCELLED	
Teamwork	45,0%
Preparing and having Presentations	20,0%
Ideation and Prototyping	15,0%

WHAT WAS SURPRISING?	
Structure and teaching methods	45,0%
PD process: challenging and rewarding	42,5%
Teamwork	22,5%
Effectivness and quality of prototyping	20,0%

OTHER POSITIVE THINGS WORTH MENTIONING	
Lectures and Teamwork	47,5%
Teamwork	27,5%
Lectures	22,5%

Table 7. The summary of the results coded from the course feedback.

4 Results I

In this section we will first go through the Publications that can also be found in the Appendix part of this thesis. Then we will look at other research results that led to the inductive inference of the O-CDIO model. The main result of this thesis research was the O-CDIO model that was developed from the results of the different phases of the action research loops. The O-CDIO model is presented in *Results II* together with the courses designed for it. The results of the present-state-analysis and the piloted courses have relevance both as stand-alone results and particularly as part of the action research loop that started in fall 2011 and lasted until fall 2015, leading to the creation of the O-CDIO framework. Figure 10 presents the thematic relation of the publications where the Publication VIII is the synthesis of the previous publications and answering to the RQ´s presented in this thesis. Figure 11 presents, which publication answered which RQ.

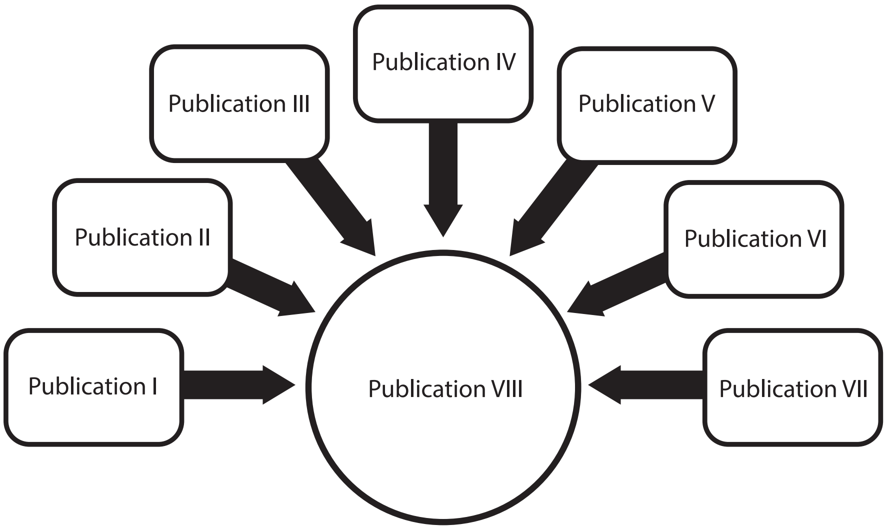

Figure 10. The Publications in this thesis presented thematically in relation to the results of this thesis research. Publications I-VII can be seen as contributing to the Publications VIII that was the synthesis for the research presenting the actual O-CDIO model and also presenting preliminary findings from new teaching methods also presented in Publication VII.

RESEARCH QUESTIONS IN RELATION TO THE ARTICLES								
	Publication I	Publication II	Publication III	Publication IV	Publication V	Publication VI	Publication VII	Publication VIII
RQ1	•							•
RQ2		•	•	•	•	•	•	•

Figure 11. The research questions RQ1 & RQ2 in relation to the Publications I to VIII.

Results from the papers published in this thesis

In this section the published papers, referred to as Publications, included in this thesis are explored from the perspective of their main findings. The five questions asked of each article are: what was the research question, what research methods were used, what were the main results, and how do the paper and the results contribute to the thesis? In addition to the publications the main results of the research that were either chronologically or thematically aligned with the publication in question, are presented together with the publication in question.

The role of the author in each publication is explicated in a separate appendix attached to this thesis.

Publication I

V. Taajamaa, K. Vilonen, "Future trends of engineering education – implementing CDIO?" ICEE 2012 Conference, Turku Finland, 2012

The first article: "Future trends of engineering education – implementing CDIO?", was also the very first article published concerning the reform process. The article studied the present-state analysis of engineering at UTU, comparing it with a similar kind of development initiative in another engineering unit at Aalto University, Finland. UTU's the students came from the departments of Information Technology and Biotechnology and Aalto University's from the

School of Chemical Technology. The article´s main contribution to the thesis is that it presents the foundation and background, which led to the construction of the O-CDIO framework presented in next section. Results of the article mainly answered RQ1 of this thesis.

Research question was: What is the difference between the CDIO Expected Proficiency Levels and the levels of the educational units researched?

The first phase of research conducted was the present-state analysis, which was performed in order to understand the development stage of UTU engineering education. Interviews and initial analysis were conducted from December 2011 to April 2012. The analysis was based on the audio-interviews with faculty, students, alumni and industry representatives. Altogether 21 faculty members, 10 students, 3 alumni, and 2 industry representatives were interviewed using semi-structured theme interviews. The interviews lasted from 45 minutes to 140 minutes. The faculty members were identified as the most important stakeholders in the change process, because they did the actual work in the reform process. The question list for the faculty interviews, can be found in the Appendix 1.

The research method included a survey of the current state of engineering education in both of the units. The group questioned consisted of students from both units and the questions were based on the CDIO Syllabus 2.0 [8]. In addition, the findings from the semi-structured faculty interviews at UTU were used as additional material for analysis. The analysis method was a mix of case study analysis with frequency distributions and qualitative analysis. There were 33 answers: 20 from UTU and 13 from Aalto.

Although the sample was small, only 33 answers, an analysis was conducted based on the CDIO Expected Proficiency Levels (EPL) [8]. The results showed that at the majority of the proficiency points the comparative EPL provided by the CDIO literature was higher than the perceived learning from the UTU and Aalto students [7]. Especially in the sections concerning ´Design´ and ´Implement´ experiences. This lead to the hypothesis, that implementing CDIO would raise the perceived EPL among the students. The main reported result concerning the UTU reform, however, was the perceived understanding among the UTU faculty of a status quo in UTU engineering that needed redevelopment. In UTU this analysis verified the need for the implementation of a CDIO structure.

The overarching finding obtained from the interview results, especially from the faculty, was that there was very little collaboration within and outside the university, some pedagogical projects were implemented in the courses, but there was precious little active learning methods *per se*, and very little industry collaboration. In addition, although the CDIO framework was a familiar name to some of the faculty members, there was no understanding of the content and goals of the CDIO framework. What was, however, evident was that the actual technical competence and expertise was at an acceptable level. The latter finding and results were later supported by the fact that only around 20% of the existing courses had to be completely redesigned when planning the new curriculum.

In summary the main results from the faculty present-state-analysis in spring 2012 were that there is little or no collaboration with other courses, teachers, departments, or industry but the curriculum for engineering education was unaligned and there was no concise vision of how the curriculum should look like. There were some pedagogical experiments but they were individual initiatives and scattered throughout the faculty and there were no overarching goals or pedagogical projects on-going. Teaching was based on lecturing: ´a talking head at the front of the classroom´ with very little or no industry collaboration at all. The technical content and competence, however, was perceived sufficient and required no major revision. There was an clear interest in implementing new teaching methods and the faculty acknowledged the need for change. All in all there was overall enthusiasm and commitment towards change.

Based on the results from the survey, and especially from the semi-structured themed interviews, there was a clear understanding that something had to be done in order to develop EE in UTU. What, how and with what resources were the main questions that arose from the interviews [Publication I]. The most urgent and important needs were identified as being in the curriculum, course structures, teaching and the assessment methods. The multidisciplinary collaboration inside and outside the university was also seen as problematic. There was, however, a clear interest in it. But a lack of time or other resources, and conservative attitudes were seen as hindering collaboration. Creating a culture where multidisciplinary collaboration is the modus operandi was seen as needing time and much concrete action, but be beneficial to all parties involved. The actual disciplinary content meaning what was being taught during the courses was perceived to be at an adequate level. Thus, the idea of paradigm change *from teaching to creating learning experiences* was well received and understood among faculty and, to some extent, among students as well. In the students' case, however, the change *from teaching to learning* awoke questions such as, *What does this actually mean?*, *How is it going to be done?*, *Does it mean more work for us?*, One possible explanation for this is that the faculty was already somewhat exposed to CDIO and to the constructive way of perceiving teaching and learning. These results further verified the need for the reform of the curriculum and the teaching methods of UTU's engineering education. The majority of students, however, had no idea of CDIO. All of the interviewed students found it important that the students were taking part in the change process [Publication I, p.5]. Regarding the students, it can be noted that they had little or no idea about the CDIO framework, nor any in-depth ideas on how the teaching or degree structure should be realized, and although they acknowledged that the situation was not ideal, they still took the status quo of engineering education as given. The students were, however, kept in the change process – though they were rarely active participants.

Publication II

V. Taajamaa, X. Guo, T. Westerlund, H. Tenhunen, T. Salakoski, "First Evolution of the Introduction to Engineering course – Case Study from the University of Turku." CDIO Conference Proceedings 2014

By 2012 there was a clear emphasis on the need to speed up the design and implement cycles and also push toward the conceive-design-implement experiences in the I2E courses [8]. This was achieved by using short Design-Implement project cycles within a very limited time frame, in practice, from 2 to 4 hours especially in the beginning of the course.

The second article: "First Evolution of the Introduction to Engineering course – Case Study from the University of Turku" introduces the results from the two first years of the I2E course which correlate with the ILOs of the course and the CDIO standards. The article´s main contribution to the thesis is that after the piloted courses the results from the learning outcomes supported the use of activating learning methods and gave evidence to further the research on curriculum development. Results of the article answered mainly RQ2 but indirectly also RQ1.

Research question: How the students understand the course's learning outcomes, and how the teaching team was able to implement the ILOs into the course structure?

The research data came from students' study journals kept during the course, the teaching team's reflection on the findings, and from a course survey based on the ILOs of the course. The method of analysis utilized frequency distribution and qualitative analysis.

Publication II presents the longitudinal results from 2013 and compares them to 2012. Very little had changed in the course structure or ILOs during that time.

Also the teaching team: the main teacher and 3 teaching assistants were the same as in 2012. The changes that did occur were in the content, where the emphasis shifted from programming theory to a more applied approach in the context of the robots used in the course. The exam was also modified incrementally and instead of seven study journals as in 2012, there were only three in 2013. Also the team sizes were smaller for 2013. All in all, after the analysis of 2012's results, no major development needs were identified for 2013. The majority of the teaching methods were a combination of active and experiential learning methods, such as competitions, role changes, reflective and open discussion inside and between the teams as well as reflective study journals [7,8,62,63].

Another important aspect was the intention to create a relaxed, non-hierarchical, and proactive atmosphere in the class. In other words, during I2E enjoying learning and having fun doing it was encouraged. An excerpt from Publication II:

> *The idea of the course is to show for the students that, as engineers, they have the chance and obligation to be constructive and they are able to build things, hands-on. From the very beginning, the doing process increases students' interests, and, at the same time, describes a general image of what engineering is all about. In addition to this, if the students are having fun, their learning is enhanced as well. Feeling of having fun engages the student to the learning process even without a student noticing that he or she is learning while doing and having fun. (Giles et al., 2010, Bisson et al., 1996.)*
>
> *The characteristics of fun are that it is relative, situational, voluntary, and natural. Fun can have a positive effect on the learning process by inviting intrinsic motivation, suspending one's social inhibitions, reducing stress, and creating a state of relaxed alertness. (Bisson et al., 1996.)*
>
> *It is the responsibility of the university, in practice the responsibility of the teaching team, to provide this experience so that students can adapt the true picture of what engineering can be. (Publication II, p.3.)*

The results showed that the results improved from year 2012 to year 2013, with those for teamwork being above expectations. Other than that, the results were as expected, the students learned about problem solving, teamwork and tolerating ambiguity. These results are well aligned with the ILOs of the course and the fact, that 87% of the student cohort felt either motivated or really motivated to continue their engineering studies was very promising.

As seen in Tables 8 to 12, the main results from 2012 and 2013 were the perceived learning outcomes related to teamwork, problem solving , and coping with ambiguity.

Below, the main results of the learning outcomes displayed in graph form.

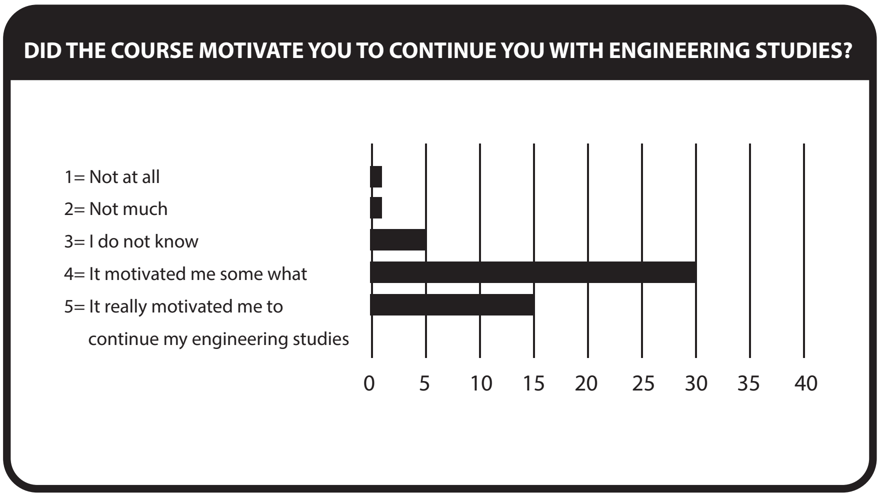

Table 8. 87% of the students in 2013 mentioned that they were motivated or really motivated to continue their engineering studies [Publication II]. In 2012 the result had been 80%.

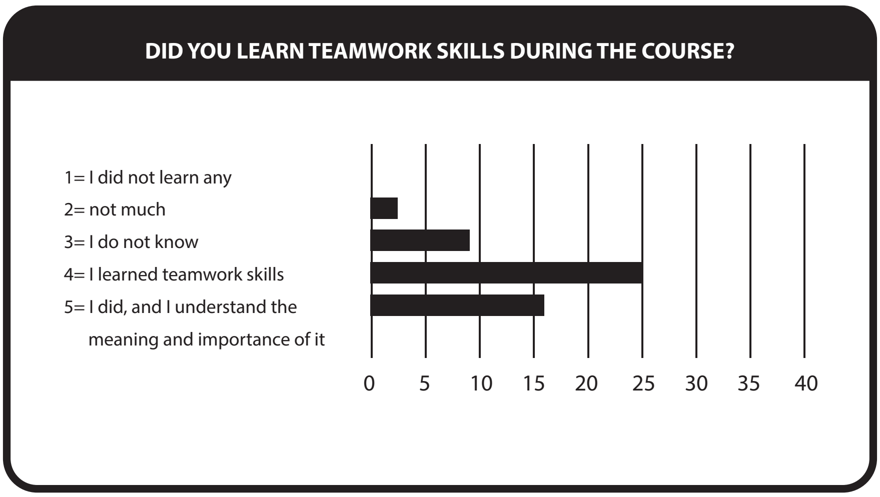

Table 9 [previous page]. One of the most important ILOs for the course is the emphasis on problem solving and communicating in a team environment, and teamwork in general. In 2013 more than 78% claimed that they learned teamwork skills, achieving one of the main ILOs for the course.

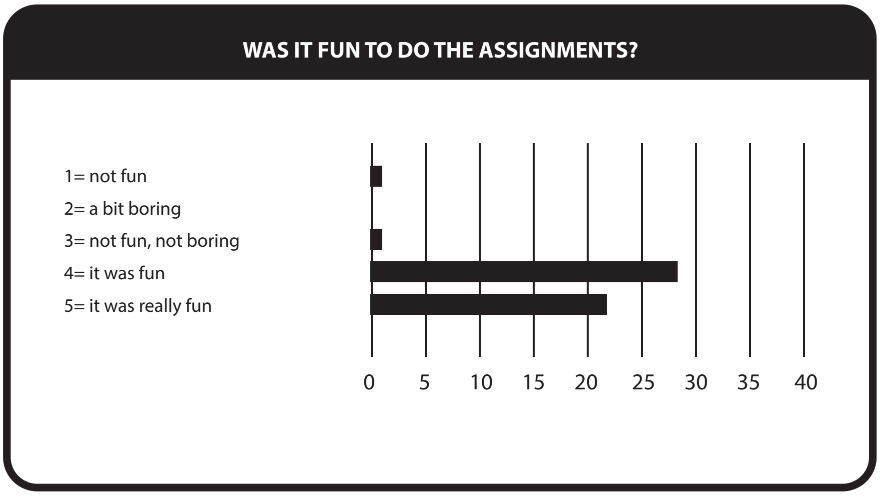

Table 10. The questions Was it fun to do the assignments? received a high ranking. In 2013, more than 96% answered that it was fun or really fun. To Was it a fun course? 96% answered that it was fun or really fun (50% gave the highest ranking of 5). Both answers gave impetus to the idea that the ILO of realizing engaging and motivating teaching methods, course content, and structure was being achieved.

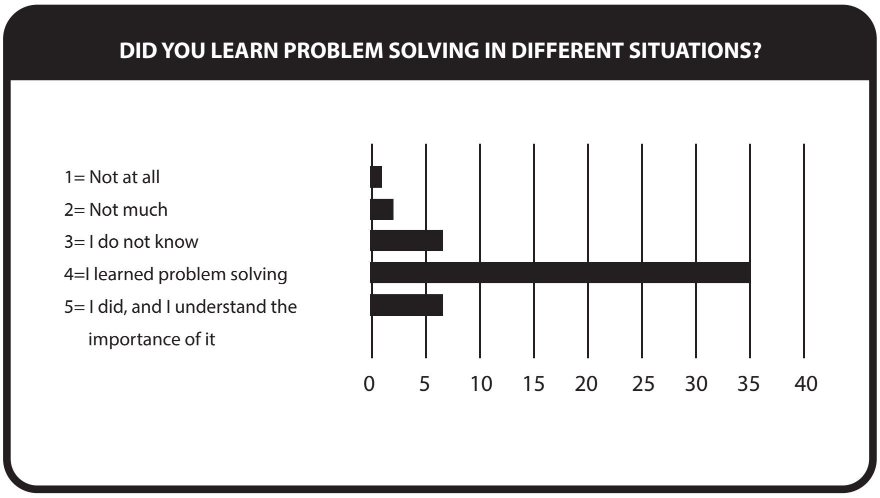

Table 11. Problem solving skills are the single most important and desired learning outcome aimed for by the course. In 2013 almost 96% of the students learned problem solving. In 2012 the figure was 72%.

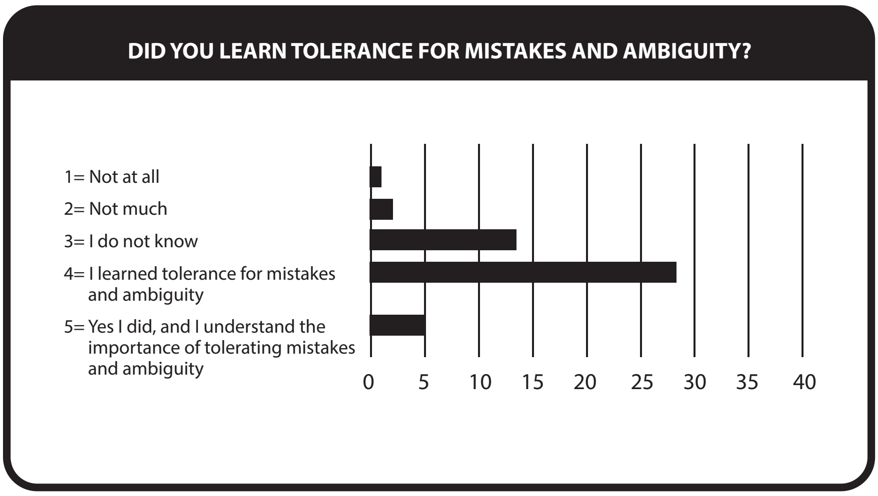

Table 12. Tolerance towards ambiguity is an important ILO for engineering students [20]. In 2013, 65% of the students claimed that they had learned tolerance towards making mistakes and become more accepting of ambiguity. In

2012 the figure was 57%. What is striking is that 25% could still not say if they had learned tolerance regarding making mistakes and tolerance of ambiguity.

In terms of the O-CDIO structure the I2E course has no major revision needs. With regard to discipline, in the future, the emphasis will be more on product development than on embedded systems or IT in general. In other words, applications, hands-on problem solving and the first building blocks for innovation are more important than IT. IT and ICT will help to provide the context, while product development will provide the disciplinary setting.

Publication III

V. Taajamaa, H. Sjöman, S. Kirjavainen, T. Utriainen, L. Repokari, T. Salakoski, "Dancing with Ambiguity – Design thinking in interdisciplinary engineering". Presented at the Design Thinking Conference, Shenzhen, China, 2013

The third article: "Dancing with Ambiguity – Design thinking in interdisciplinary engineering" introduces the results from the piloted capstone course *Future*, which is presented in: PART III Capstone 1 and 2: Future and Nightcap. The main contribution of this article to this thesis is that it gave evidence of how the open-ended Master´s level project –courses can be run in an international context. These Capstone articles acted as prototypes or pilot courses for the RDC –course later presented with the O-CDIO framework. The results of the article shed light on mainly to the RQ2 of this thesis.

Research question: What kind similarities and differences are there in terms of learning outcomes between two capstone project courses?

The paper introduces the future capstone results, comparing them with the results from another capstone course ME310, which is run by the Department of Mechanical Engineering, Stanford University, USA. The courses shared similar ILOs [135]. However, they were at different phases of evolution, and although the pedagogic approach was similar, the applied methods were different. Furthermore, the data for the research came from students who had graduated less than six months ago. The interview data for the Stanford course came from students who had graduated between one and eight years ago.

The research data consisted of thematic semi-structured interviews, study journals and surveys. Both courses were analyzed separately but with a similar method. The analyzed results were compared and four interlinking themes, although with different emphases, were found. The themes were: a) communication, b) self-discovery and working methods, c) the design process, including different phases of the course and project process and d) the entrepreneurial mindset and attitude towards failing that was achieved as a learning outcome as part of the course. The results show that the aimed for learning outcomes for both courses were achieved and there was significant personal growth during the course. Also the multi- and interdisciplinary team setting provided a platform where the students learned to appreciate the opinions, knowledge and skills of students from other disciplines. There were differences as well [136,137]. The students on the ME310 course learned significantly more about prototyping. Also their personal growth and attitude towards failing was reported higher than those on the UTU capstone course.

The findings of this article had a clear impact on the creation of the Radical Design Challenge course presented in Results II, providing a platform for testing interdisciplinary and international student and teaching team collaboration.

Results from other piloted Capstone courses at UTU

The first capstone experiences influenced the reform process as well as there was scientific evidence that the new methods work. After the first Capstone another pilot capstone was launched to gather more data and experiences of the course structure and teaching methods. Below the main results from the comparison of the two UTU born Capstones.

The research on the two piloted capstone courses focused on discovering whether students learn relevant and transferable working life skills in an interdisciplinary and open-ended project setting. Interdisciplinary in this context means a teamwork setting where students work jointly to create a coherent and holistic solution by analyzing, synthesizing and harmonizing different disciplines [26,136,137]. The difference compared to multidisciplinary and transdisciplinary is that: in a multidisciplinary setting the students work toward the same goal, but in their own disciplinary silos. They work in parallel and at the same rate of time and in the same time sequence, but separately. In a transdisciplinary setting the students share the same conceptual framework and all the disciplinary boundaries are crossed and made transparent. In an interdisciplinary setting they all work around the same problem and do so together but through their disciplinary knowledge, skills, values, and lingua [26,136,137]. It is important to remember that there is an abundance of disciplinary definitions. For example, cross-, intra-, conceptual-, synthetic-, multi-, inter-, and transdisciplinary, etcetera [26,136,137]. These definitions are often used without clarification about what is meant and in what context. Second, the whole setting is artificial. The university is divided into disciplines, but the world and especially the world of open-ended problem solving is not. In this thesis we use multi-, inter-, and transdisciplinary terms and these definitions should not be used interchangeably [26,136,137].

The students invented the names for the capstones projects themselves. Future stands for *Fudan and UTU Reinventing Education*. The Future Capstone prompt was to redesign the learning experience of mathematics for high school students and the team combined students from both UTU and Fudan University, Shanghai, China. The FUTURE name was later adopted to mean the whole ICT double degree programme which Fudan and UTU have developed.

Nightcap came from the challenge, which was to increase the night time safety of the elderly people in a municipal elderly home and the safety of the nurses. The Nightcap project included students from the nursing sciences and from the Turku University of Applied Sciences. Team FUTURE had students from eight different disciplines, five of them being non-engineering disciplines: microelectronics, embedded computing, computer science, marketing, finance and accounting, futures studies, educational sciences and East-Asian studies. The Nightcap team had students from four different disciplines, two being non-engineering disciplines. The research data in the capstone projects came from:

Capstone 1: *Nightcap*: feedback during and after the course, study journals, and an interview with the project manager after the course

Capstone 2: *Future*: interviews, study journals and feedback during the course, interviews and feedback after the course

The teaching method in both of the capstone courses was the same: a combination of integrative- and action-based teaching methods, mainly the PBL and POPBL approaches. The applications of the method varied to some extent due to the structure and timeline of the course. This was partly due to practical reasons and partly because it gave an opportunity to realize comparative data. The Future Project lasted nine months and Nightcap around six months. The goal and the ILOs for both of the courses were the same. The main focus was on acquiring relevant working life skills and creating a setting whereby students could learn to identify their strengths and weaknesses as engineers, as students from other disciplines and as team members. The assessment of the capstone projects followed the same criteria as well and were followed by an analysis of the problem, prototyping and proof of concept, communication with and to the stakeholders, and the innovativeness of the solutions. The assessment took into account the study journals, workshop results, presentations, customer feedback, and other documentation.

The main results of the Nightcap Project are presented below. The project lasted six months instead of the nine months that was the duration of the Future Project. All the students involved in Nightcap were Finnish, although from several different disciplines and two different institutions: electronic engineering, software engineering, nursing sciences, and sustainable development. Also, there were five students in Nightcap, instead of the ten in the Future Project.

The results from the Nightcap Capstone Project show that interdisciplinary learning occurs both on an individual and on a team level as seen in Figure 12.

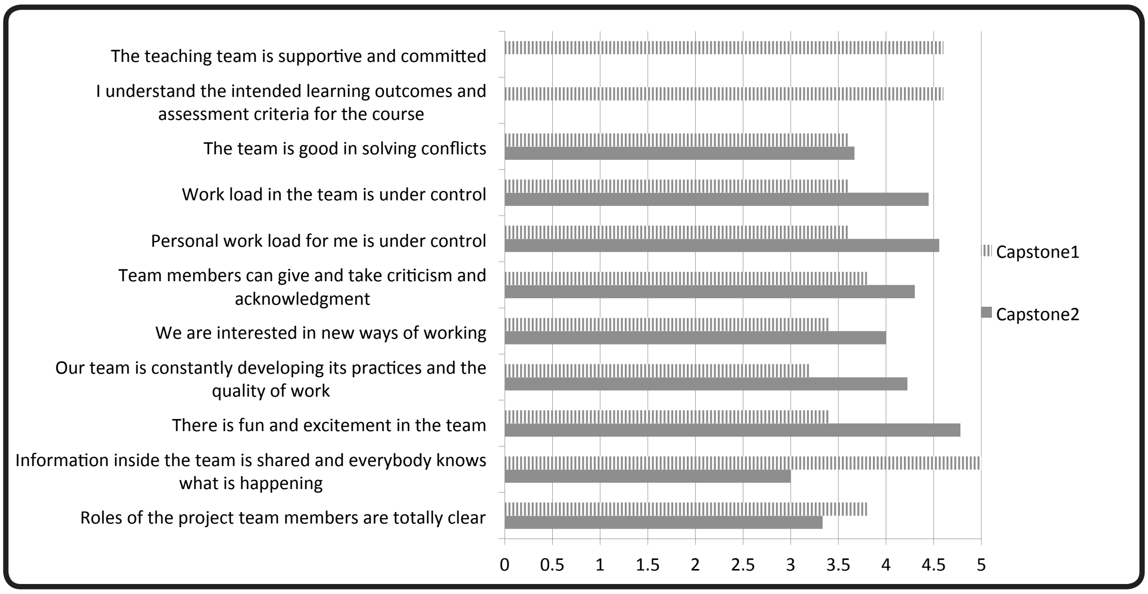

Figure 12. Comparative data from the Nightcap and Future projects. In the figure 0 represents the lowest grade and 5 is the highest. The questions were based on the ILOs of UTU's capstone projects. The main findings of two different courses are that the role of communication in Capstone1 (Nightcap) was clearly higher. The explanatory factors include the fact that there were only five team members instead of ten and all spoke Finnish as their mother tongue, plus the project was located in one region, the Turku area. For Capstone2

(Future) fun and excitement, i.e. engagement and motivation, helped to keep the students developing their practices and work quality. Both teams had similar conflict solving skills and both could give and accept criticism and praise.

For the students in the Nightcap project the main difficulties were in transdisciplinary professional skills such as communication and project management. These results lead to the conclusion that the RDC course should be run for at least six months if not the whole academic year and that the interventions from the coaching team should be kept constant.

Publication IV

E. Rautavaara, V. Taajamaa, V. Lyytikainen, T. Salakoski, ”Learning outcomes of a project-based capstone product development course.” Norddesign Conference 2014, Finland

The fourth article: “Learning outcomes of a project-based capstone product development course” presents the results of an established capstone course called Project Development Project (PDP), held in the Design Factory of Aalto University. The paper reports the results of a study that analyzed the course structure, teaching philosophy and the learning outcomes of a PDP course designed to provide relevant product development, project-based teamwork and project management skills. The study looked into the learning outcomes achieved during the course in relation to its ILOs. The data for the study consisted of eleven thematic semi-structured interviews. The main contribution of the article to the thesis is that is that first is supported the findings from the other Capstones piloted in UTU and also gave a point reference how Capstones could be run in the O-CDIO framework so that it involved more students. The results of the article answered mainly RQ2 of the thesis.

Research question: How do the perceived learning outcomes relate to the intended learning outcomes in a capstone project course?

The results show that the ILOs were achieved. Students were able to construct meanings and understand how the different projects phases work and how to achieve successful team-based project work in the context of product development. The six main themes that arose from the data were the importance of project management and understanding the role of the team members, importance of teamwork and team building, importance of good communication and interaction between people, importance of being proactive and making things happen, difficulty of working remotely in an international environment, and understanding the basics of product development and the importance of prototyping and ideation

The main contribution of this paper was to further understand how the capstone experience can be made as effective as possible. Also, the team setting in the PDP course is somewhat different than that in the piloted UTU capstone and ME310 courses. In essence the role of the project manager is more prevalent.

The study gave relevant data for the creation of the Radical Design Challenge – course presented in the Results II section. Reflecting on the lessons learned from a similar course but held in another university and in a different context re-affirmed the need for the need of focusing to the first phases of the product development process. In practice to the identification phase in a team environment.

Publication V

A. Jarvi, V. Taajamaa, S. Hyrynsalmi, "Lean Software Startup – an Experience Report from an Entrepreneurial Software Business Course," The 6th International Conference on Software Business, 2015

The fifth article – "Lean Software Startup – an Experience Report from an Entrepreneurial Software Business Course" presents the results from a project course that shares similarities in terms of structure, methods, assessment, and content with the piloted UTU Capstone, Bootcamp and Project management courses. It reported the experiences from three years of running a project course aimed at engineering and business students. The course focuses on software business, the lean start-up model, teamwork and entrepreneurship. The article describes the pedagogical design and the actual implementation of the course. The main contribution of the article to this thesis is how the activating teaching methods worked in another disciplinary context than product development and implemented with other than design thinking based methods. The results of the article mainly answered RQ2 of this thesis.

Research question: What learning approaches do the students use in a team based start-up course?

The data for the course came from questionnaires, student learning diaries and the reflections and knowledge gained by the teacher. The method of analysis followed a version of case study analysis.

The results show that the students learned considerably from other members of the team. Another source of learning was the mentoring. Neither of the answers is a surprise, yet it is good to acknowledge that students do benefit from a team setting. This indicates that by investing in teamwork, the teacher actually facilitates student learning. Another interesting result is that the early phases of the project were the source of most learning. The *idea generation and business development* was found to be a phase where there is ambiguity and creative idea generation is needed. This supports the idea of the O-CDIO framework, where the emphasis is on the early phases of the engineering lifecycle.

The article provided an important perspective on how active learning methods and a project-based team setting works in an IT context. The results support the importance of focusing on the early phases of a project's lifecycle, especially if novel ideas and innovations are sought.

In the lean start-up course the teaching method is based on an experiential learning approach similar to the capstone course [104,136]. Being one of the culminating learning experiences the design process of the Radical Design Challenge -course benefitted from having comparative data from as many different capstone – courses as possible. Publication V contributed to the design of the Master´s level learning experiences of the O-CDIO framework.

Publication VI

X. Guo, V. Taajamaa, K. Yang, T. Westerlund, L. Zheng, H. Tenhunen, T. Salakoski: "CAPSTONE BOOTCAMP CONCEPT CATALYZING PROBLEM-BASED LEARNING." CDIO conference 2015.

The sixth article, "CAPSTONE BOOTCAMP CONCEPT CATALYZING PROBLEM-BASED LEARNING" presents the results of the Capstone Bootcamp course held in summer 2014 for the UTU and Fudan University, China double degree students. The article presents the background and need for the course and the structure and teaching methods used. The data were collected using interviews and surveys together with observation. The semi-structured group and the individual interviews were conducted before and after the course. The analysis was made using case study analysis. The main contribution of the article to this thesis was that based on results the Bootcamp course became a part of the O-CDIO curriculum and in that way was part of the answer to both RQ1 and RQ 2 of this thesis.

Research question: What learning outcomes does the Capstone Bootcamp - course catalyze in terms of transdisciplinary working life skills?

The Capstone Bootcamp summer course was initially planned to act as an introductory course for the Capstone Course, which the students were obligated to take in the following fall. It was also designed according to the feedback from the students participating in the degree program. According to the feedback, they were unused to active teaching methods and hands-on learning. The Bootcamp was held during summer 2014.

The research data for the Bootcamp course consisted of semi-structured audio interviews before and after the course. Both interviews were done in a team-setting. There was also a survey that the students filled in after the course. The results showed that due to teamwork, communication skills were enhanced. That was interpreted as a developed tolerance towards ambiguity and open-ended problem solving, both being key thematic learning objectives for the course. However, a week of preparation with a lecture and a mini-research project, plus a one-week intensive Bootcamp experience were not enough to make this learning objective explicit to the students. Instead, the student’s answers are related to the exercises and reflect learning as it related to them, see Table 13.

QUESTIONS	THEMES PROPOSED BY STUDENTS	NO. OF OCCURRENCES
What were the most valuable/important things you learnt from the Capstone Bootcamp	Teamwork (communication, cooperation, mutual trust)	8
	Presentation skills	8
	Knowledge of the Capstone Project	2
	Others (time management, self-knowledge, English language skills)	3
How do you think the experiences and skills you learnt from the Capstone Bootcamp will help your future in terms of studies, working life, or life in general	Teamwork (communication, cooperation, explore merits of team members, management skills, mutual trust)	8
	Presentation skills	5
	Others (innovation capability, tolerance of ambiguity, self-knowledge of own shortcomings and merits)	3
	Not sure yet	3

Table 13. Interviews regarding the most valuable/important things learnt from the Capstone Bootcamp. (2, p. 8.)

The actual perceived learning outcomes differed somewhat from the intended learning outcomes. Communication, including teamwork, cooperation and the building of mutual trust, were perceived to be the most valuable outcomes of the course. In addition to the results above, the students felt that they better understood what the capstone experience entailed.

The contribution of the article to the O-CDIO model and to this thesis is twofold. Although the initial perceived learning outcomes did not match the intended learning outcomes set by the course, they did emphasize the importance of team building, communication and design thinking methods. Second, the course in itself proved to be well designed and suitable for combining with the RDC, capstone or just as a stand-alone course.

Publication VII

M. Eskandari, V. Taajamaa, B. Karanian, "Tell/Make/Engage: Design Methods Course Introduces Storytelling Based Learning." American Society for Engineering Education 2015, Seattle USA.

The seventh article, "Tell/Make/Engage: Design Methods Course Introduces Storytelling Based Learning" presents the results from a Stanford University course which aimed to develop the abilities of students in active and socio-reflective storytelling. The goal was to engage the students in a process where they learn communication skills by working in a team setting. The Stanford course is especially designed to enhance communication and team skills in an entrepreneurial start-up setting. The article also presents the work-in-progress *Storytelling Based Learning* for the first time. The contribution of the article to this thesis is of paramount importance. The results of the paper gave confirmation that an affective-emotional learning process can be achieved for engineering students as well and that the learning method can be used in engineering education.

The paper studies the relationship between active storytelling concepts and individual responses. The course Tell/Make/Engage is a design methods course that focuses on delivering experiences to the students to positively influence their self-efficacy [85]. The students also learned how to identify needs to create successful start-up projects.

Research question: How do we coach and lead students to recognize their full potential as individuals and as team members to not only learn new knowledge and skills but also to help them transform as they lead, start-up, and become members of the global society?

The results show that there is a possibility for misunderstanding if commonly used rules of communication are used. Hence it is important not to repeat for perfection. The study showed that flawless storytelling is not believable.
It is also important to interact with a large audience rather than one-to-one. It was found that spontaneous storytelling and a personal and unique style of leadership may work better with large audiences. There is neither any need to apply a template to tell and memorize a story. Instead one should start from the middle and find a new beginning from there. The use of generic stereotypes should be avoided. Both young and old people prefer to hear personal and emotional stories that they can relate to.

Storytelling and storytelling-based learning are powerful socio-cognitive learning processes. Storytelling-based learning is founded on decades of experience within well-established disciplines, such as social psychology and the arts. The impact that storytelling and storytelling-based learning had on the research project and the O-CDIO model was important as it emphasized the importance of seeing the learner as something more profound than just a rational and cognitive person. The role emotions play in learning is fundamental and especially so in the case of early phase product development and project management.

Publication VIII

V. Taajamaa, M. Eskandari, B. Karanian, A. Airola, T. Pahikkala, T. Salakoski, “O- CDIO: Emphasizing Design thinking in CDIO engineering cycle.”, International Journal of Engineering Education Vol. 32, No. 3(B), pp. 1530–1539, 2016.

The eighth article, “O-CDIO: Emphasizing Design thinking in CDIO engineering cycle”, presents the final result of the research project leading to this thesis. This is the O-CDIO model, which is the synthesis of the piloted courses, the literature and the research related to the reform of EE at UTU. The model itself, seen in Figure 13, is based on the well-established CDIO model and emphasizes a human-centered approach for the engineering lifecycle in addition to systems thinking based on the natural sciences.

Research question: What kind of degree level framework could combine human-centered methods and processes to natural sciences based education during both BSc and MSc studies?

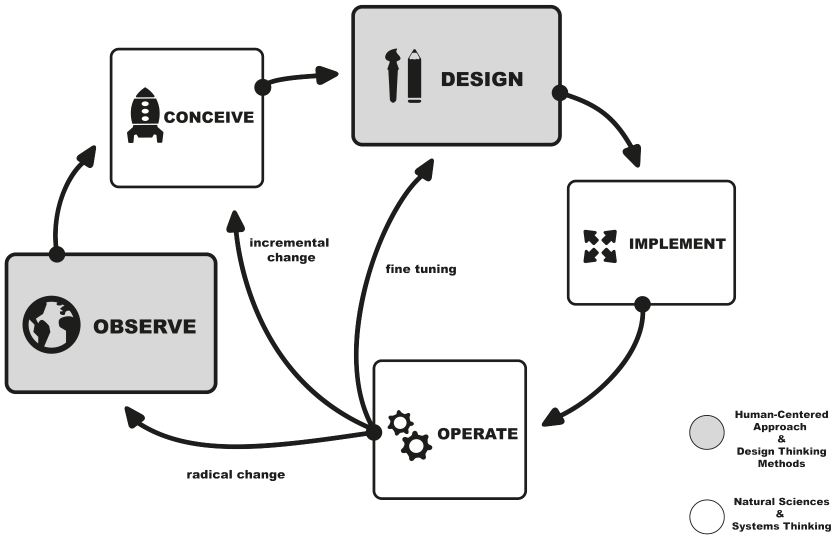

Figure 13. The O-CDIO model compared to the CDIO model, which is the basis of the O-CDIO model. The O-CDIO model is described in more detail in the following sections.

The paper also presents results from the two pilot course structures and four courses altogether. The idea is to elaborate on the kind of research that has led to the creation of the O-CDIO model. The data gathered from these courses were again based on both qualitative and quantitative sources, such as semi-structured interviews and questionnaires or surveys. The data were from the I2E courses from 2012 to 2014 and from the prototype PDRP course from spring 2014. The methods of analysis included a set of statistical analysis tools, case study analysis, reflexive pragmatism and a qualitative analysis of the texts.

Publication VIII demonstrates the O-CDIO model for the first time and elaborates on its key points. The role of Publication VIII to the whole thesis is central and it can be viewed as a synopsis of the whole dissertation. Working with researchers and auditing the courses at the d. school at Stanford University proved to be a key factor in the process of its creation [102]. The work with Dr. Karanian also spurred the understanding that learners are emotional actors as well as cognitive processors of information [138].

5 Results II, Design thinking in Engineering Education – The O-CDIO Framework

> *My primary advice regarding engineering education is that making universities and engineering schools exciting, creative, adventurous, rigorous, demanding, and empowering milieus is more important than specifying curricular details. (C. M. Vest, 15.)*

In this section we introduce the O-CDIO framework, the main result of this thesis research, which was induced from the research results. The O-CDIO framework adds human-centeredness and human-centered approaches to the natural sciences-based engineering education. In practice, this happens by restructuring the curriculum, rearranging the syllabus, the course level structure and the content, and course level ILOs, as well as by introducing both existing and new teaching methods into the actual learning situation. The model is a synthesis produced by active discourse and reflection on the data of the pilot courses and the relevant literature. It is important and interesting to note that non-scientific literature and normal activities have had a prominent role in the creation process [e.g.39,140]. Though literature in this section is cited widely, the O-CDIO framework is a stand-alone result of the thesis and created solely by the author. The last part of this section highlights the *Observe* elements of the O-CDIO model.

The implementation of the O-CDIO framework is discussed in section 6 the Conclusion and Limitations. The research questions RQ1 and RQ2 are also answered in the same section.

All of the independent and interdependent parts of the O-CDIO model are re-invented from existing approaches. In itself, there are no new parts or modules in the structure, epistemology, or teaching methods, excluding the Storytelling-based learning (SBL) method. Hence, the O-CDIO model is a redesign of existing models. The O-CDIO's innovation is in *how* the different parts are constructed to serve the purposes of university level engineering education. It is the context and the way it is built that makes it unique. It is important to acknowledge that the O-CDIO framework and model has two levels of abstraction. First, the epistemological and philosophical stance it takes within the world of existing engineering education models. Second, the concrete and pragmatic curriculum and learning methods that it introduces. In practice, this means a heavy focus on the first phases of the engineering lifecycle, where the emphasis is on problem identification and the use of human-centered design thinking methods. It also means that the suggested course structure and learning methods are intended to be prototypes that will continually develop in response to the needs they serve.

O-CDIO as a Framework

The O-CDIO model has never been implemented as a whole and although all of the suggested courses have been prototyped and piloted, their alignment as a whole is proven only in theory. The O-CDIO model has been created to answer to both RQ1 and RQ2 presented in the Introduction section. There was a real and identified need to educate engineers not just to engineer brilliantly but to also create innovations. If that is to happen, the natural sciences are not enough; human-centered approaches – that span the problem space, create new markets and recognize the latent needs of users and customers, while designing and implementing required solutions – are needed. The O-CDIO model, created by author of this thesis, is designed to fulfill those needs.

The O-CDIO framework is based on and builds on the well-established CDIO EE framework [8,24]. The first 'O' in the O-CDIO stands for the *observe* phase, which is presented in more detail in section 5.3. The CDIO is an education model that was conceived and implemented to answer the needs of engineers who can actually engineer in addition to knowing their math, physics, and other natural sciences. The CDIO is based on the same philosophical foundation as the O-CDIO model, namely social constructivism, which stems from cognitive and social psychology [86,88]. It utilizes problem-based learning as its main approach to teaching [141,142]. The CDIO model has problem identification or the conceiving phase embedded into it, yet the focus is on the ´Design´ and ´Implementation´ phases of the engineering lifecycle [7,8,24]. O-CDIO adds considerable focus to the problem identification phase by using human-centered approaches to achieve that (see Figure14). This *design* phase is also conducted using human-centered design thinking methods, such as observations, prototyping, and storytelling. The goal of the design phase is to transform the complexities of the problem space into a palette of possible solutions that can be communicated and implemented in the *implement* phase [e.g. 20,21,71,143]. In the O-CDIO model the emphasis is in the *observe* and *design* phases, which are seen as the main phases of the engineering lifecycle aimed at creating radical innovations.

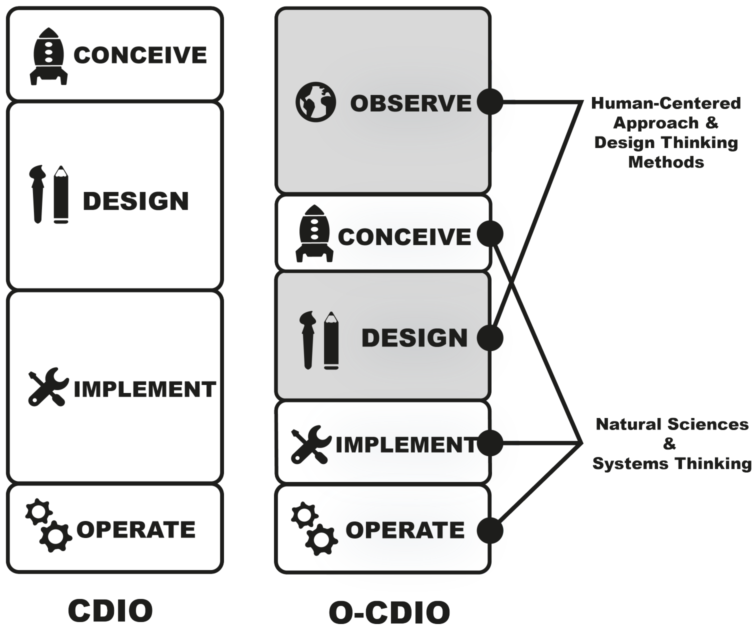

Figure 14. The traditional CDIO lifecycle compared to the O-CDIO cycle. The O-CDIO lifecycle has a clear emphasis on the front end of the engineering lifecycle as the CDIO lifecycle emphasizes the design and implement experiences [7,8, Publication VIII]. In the O-CDIO model the ***observe*** *phase is dedicated to identifying the actual problem space, finding latent customer needs, and creating radical first concepts for future iteration. This happens by using, for example, rapid prototyping and storytelling methods [23,97]. In addition to the natural sciences-based deductive and logical thinking the design thinking methods aim to stimulate the ideation process through inductive and emotionally holistic learning methods. It is the combination and active sequence of divergent and convergent thinking that produces new unprecedented results [20-22]. The emphasis of the O-CDIO model is clearly on the early phases of the engineering cycle. The second phase where human-centered approaches are utilized is the* ***design*** *phase where the problem space is translated into a solution space.*

O-CDIO framework phase by phase

The O-CDIO activities are close to the activities in the CDIO framework. In Table 14, the main functions and phases of both the CDIO and the O-CDIO models are compared to each other.

	CDIO		O-CDIO
Observe	*Not dealt with in the CDIO framework [Authors note]*	**Observe**	Discovering explicit and latent needs that different users, the markets (it might not exist yet), and customers have. Possibly finding new potential user groups. Using needfinding, rapid prototyping and storytelling to understand the boundaries of the problem space, and then going beyond them and moving the boundaries
Conceive	Customer needs, considering technology, technical and business plans, enterprise strategy and regulations.	**Conceive**	Synthesizing the latent, market, and user needs with customer needs, conceiving the entire problem space, communicating the problem to all of the stakeholders, possibly more prototyping [23].
Design	Creating a detailed information description of the design, the plans, drawings, and algorithms	**Design**	Using, for example, prototyping, bodystorming and storytelling methods to understand the entire solution space [20,30,21]. Communicating that to the customer through prototypes and user stories. Turning the chosen solution into an action plan by using the CDIO-model with an emphasis on prototyping. In addition to the technical plan, creating a user story, visual design and business case will help support the solution.
Implement	Transforming the design into a product, process or system including manufacturing, coding testing and validation *Notice the emphasis on the technical aspects of the product. [Authors note]*	**Implement**	Prototyping, prototyping, and prototyping. Choosing the resolution and function of the prototype depending on the different aspects of the product's functionality, user and customer needs [23]. Then the product is close-to-ready for manufacturing and final tests with potential users. Otherwise, it follows the CDIO-model
Operate	Using the system to bring intended value. Maintaining, evolving, recycling and reiterating the system	**Operate**	Following the CDIO model and collecting relevant user and customer feedback, prototyping new versions and challenging the existing model by redefining and redesigning the product, process or system.

Table 14 [previous page]. The O-CDIO and the CDIO activities compared to each other. The two distinct emphases that the O-CDIO model has compared to the CDIO model are first in the ***observe*** *and second in the* ***design*** *phases. These phases utilize human-centered design thinking methods in addition to natural sciences based systems thinking [7,8]. The O-CDIO adds emphasis to the phase where the problem space is spanned. If the* ***observe*** *part focuses on the spanning of the entire problem space, it is the* ***design*** *phase that focuses on the spanning of the solution space. In essence The O-CDIO model adds emphasis to the early phases of the engineering cycle in order to create radical innovations and solutions instead of incremental ones [Publication VIII, p.26].*

O-CDIO: Course Structure, Methods and Intended Learning Outcomes

There are well-established examples of approaches where O-CDIO or human-centered approaches are combined in the engineering education context Typically, these include a learning space dedicated to this approach as well [3,5,102,104]. At the university level this approach was found not to exist.

In this section the O-CDIO course structure, examples of the course level, and intended learning outcomes are introduced [143,144]. The courses in Table 15 are all work-in-progress courses though all of them except for the Bachelor level capstone course are piloted and prototyped. The idea of the course list and intended learning outcomes is, first, to give a tangible idea of what the O-CDIO model could be in practice. Second, it aims to elaborate on what kind of courses the piloted courses have been. In the PDRP course section, the topic of prototyping is also discussed in more detail. The reasoning is that prototyping is one of the key skills and mindsets in the O-CDIO approach.

> *The aim of the integrated human-centered curriculum is to provide students with a constant stream of inspiring and thought provoking courses throughout the curriculum. Integrated disciplinary learning objectives that have human-centered approach based learning outcomes such as storytelling, needfinding, and prototyping provide the students a possibility to get immersed in an open-ended space of unrevealed needs and opportunities big and small. In essence* ***an engineer has to learn problem defining in addition to problem solving*** *[25,26]. (Publication VIII, p.4-5.)*

Bachelor level	Course	Credits
1st year	Introduction to Engineering	5 ECTS
2nd year	Product Development and Rapid prototyping	5 ECTS
3rd year	Capstone project including BSc thesis	10 ECTS
Master´s level	**Course**	**Credits**
1st year	Storytelling and Needfinding	5 ECTS
2nd year	Bootcamp & Radical Design Challenge	15-30 ECTS

Table 15. Course level curriculum in the O-CDIO framework. In this context, the framework follows the Bologna model [34]. The O-CDIO courses can be integrated into the overall degree structure or be taught as separate courses, modules, minors or majors. Minor's and major's fit well under the disciplinary umbrella of either product development or project management. An important part of the curriculum's structure is that it contains practical learning-by-doing and observe-design-implement education throughout the curriculum, instead of just in the beginning and at the end of studies [12,17-19].

Introduction to Engineering – I2E, 5 ECTS

Introduction to Engineering is a well-established course format. The idea is to give students action-based first-hand experience and knowledge on engineering [2,12]. In the O-CDIO context, I2E is all about problem solving in a teamwork-based engineering context [39,146].

The tasks vary during the course. Final competition is where students compete with football robots in a prototyped arena. Each team has a robot that uses artificial intelligence while the other robot can be steered using a bluetooth connection or similar. Students do several presentations during the course in which they are peer-to-peer assessed by other students. The results show that the students are more engaged in the learning situation when they can influence the assessment and actively participate in the learning process. (For further reading please refer to Publication II in the Appendix.)

I2E focuses mainly on the C-D-I phases of the CDIO and O-CDIO processes through assignments that are semi open-ended and competitive [8]. In this context, semi means that the assignments are engineering tasks instead of holistic open-ended real-life problems. Lego-robots were used in the piloted I2E courses to facilitate the learning process. Competitions or assignments consisted of tasks such as *build a sumo-wrestling robot* or *build a robot that can play football using artificial intelligence*. Ambiguity was emphasized through the open problem space, as students needed to choose from several different solution spaces. One wrestling robot can look very different from the other yet still be very effective. The important thing to notice is that the tasks are engineering challenges. The robot's appearance or the functions of the robot do not have any societal or business impacts. So, although I2E included identifying needs, storytelling, and other design thinking methods, the context and environment was both explicitly limited and defined to engineering. The I2E course also had personality tests and teamwork profiles as part of the course content. The idea was to engage the students and make sure that they paid attention to teamwork and especially communication within and outside the team from day one [39].

The I2E courses have been around for quite some time, and their effect, and results are well and widely reported in the EE research domain [8,12,16,146]. The reason for having such courses is to help the students realize the importance of problem solving and the project- and team-based approach to engineering during their freshmen year, then the prognosis for the whole of their study is improved [146]. Student retention also increases [39,41,147]. The I2E course in an O-CDIO context, mainly focuses on the C-D-I phases of the process. Design thinking methods are introduced through assignments in which students ideate, design and build robots that can perform tasks in a team and competition setting. The assignments for the I2E course are developed by using CDIOs, ILOs, introductory courses, the relevant literature, design thinking methods, and lessons learned from similar courses [2,8,39,39,146]. Weekly assignments with restricted timetables were found to increase the student's tolerance of ambiguity. Assignments with an open problem space forced the students to choose from a palette of possible solution spaces before deciding on a single solution space. The I2E course typically runs throughout the fall semester.

The ILOs for the I2E have changed very little since the first design and implementation of the course. The main goal is to orient the students to understand that engineering is about problem solving that mostly takes place in a team environment. Another important aspect concerns communication skills. Regarding personal and interpersonal learning results, the main personal skills that are emphasized during the course are: problem solving, time scheduling, tolerance for ambiguity and the ability to apply theory in practice. For interpersonal skills the respective skills are: teamwork, project planning and communication, and the capability to apply theory to practice. Below is a list of the ILOs, first created in spring 2012 and they are listed below:

1. During the course the students will learn how to analyze, create possible solutions and implement them in multifaceted engineering problems.

2. After the course the student will have preliminary readiness for small group work in a project environment.

3. Project work will include understanding the planning phase, project management and communicating the achieved results – textually and verbally.

4. The student will also learn how to manage and prioritize time planning.

5. During the course the students will have the opportunity to recognize and develop the substance of their education and their personalities.

6. During the course the students will learn about education and will learn to trust their abilities to solve problems

7. The assignments and themes will change on a weekly basis and they will contain tasks and competitions that will develop the ability to envisage problem setting, the design of solutions and the execution of solutions.

8. The course will contain individual student assessments, self-assessments, and the building of a personal portfolio, i.e. personal strengths, work capabilities, etc.

9. During the course the students will apply for different roles.

10. To pass the course, the student must pass a written exam and weekly assignments.

List 3. The ILO´s of the IE2 –course [Publication II].

The main learning outcomes that were developed by the teaching team in 2012 were also approved for 2013 [7,39]. The ILO´s produced a shortlist that focused on the core of what a UTU engineering education believes an engineer should know and what skills they should possess. These skills were the ability to understand the engineering process, to be motivated about engineering, to obtain the ability to solve problems, to act as a part of a team (three musketeers), to develop the ability to tolerate uncertainty and failures, to create schedules and prioritizing work and finally the ability to learn by doing [Publication II p.4-5].

Product Development and Rapid Prototyping, 5 ECTS

The Product Development and Rapid Prototyping course (PDRP) was developed from a basic lecture-based introductory course to project management theory. The whole approach was changed, including the course structure, content and teaching methods. It was designed to include rapid prototyping exercises, hands-on product development, and storytelling and communication exercises in addition to theory, and all within a project management and team-based setting. The only things that were kept from the original course were the timetable, which was eight weeks, and the context of project management. PDRP is aimed at teaching product development in a project management environment and in a team-based context by using design thinking methods, such as needfinding, prototyping and storytelling, in order to create new products. The rationale and aim was that instead of educating the students so that they learn theory, they learn the skills required for being an engineer. In other words, rather than becoming engineers who know project management and product development theory, they become engineers who can actually create new products and manage successful projects in a product development environment.

One of the core processes of design thinking is the acceleration of the ideation process, and the creation of new knowledge. In other words, *accelerated learning* [20]. This is achieved by creating instances of change at critical junctures with the goal of producing tangible prototypes and then pitching them to potential users and customers [20]. The prototypes also allow for user testing and thus more feedback. Ultimately, the rate of learning can be further accelerated by cross-team ideation and reviewing. To achieve that, collaborative tools and physical space are required [20,148] and these aspects are emphasized in PDRP throughout the whole course.

> *All the lectures consisted a hands-on exercise and during week 6 and 7 lectures were devoted to hands-on work with the projects students had created from the open-ended prompts. During the last lecture final prototypes were presented and assessed from the perspective of feasibility, viability and desirability. (Adopted from Publication VIII, p.6.)*

Capstone project and BSc thesis, 10 to 15 ECTS

Bachelor level capstone courses have not been prototyped or piloted as part of this research project, but Master's level capstone projects combined with individual thesis projects have. Furthermore, they have shown promising results [5]. However, Master's level capstone courses can be seen as too late in the degree structure to act as a deciding and integrating factor for engineering studies [12,17-19]. Other courses based on the O-CDIO approach and with the process aligned to whole the curriculum are required. This is one of the main aspects of the O-CDIO model; it uses design thinking processes, and methods as the glue to integrate the degree, helping engineering students address interdisciplinary issues, while placing transferable working life skills, and social and cultural issues throughout their studies.

In the O-CDIO framework the Bachelor level capstone project is designed to start during year three, which is the last year for Bachelor studies in the Bologna Model [34]. As seen in Figure 15, all teams start together during the first quarter of the fall semester. After the initial teamwork and team building activities, the first task is to identify problem and solution spaces. Then to design a solution, after which the implementation task is divided between the team members so that everyone receives an individual project the size of a BSc thesis (8 ECTS). During the first quarter, all the teams participate in a 2 ECTS bootcamp, which focuses on design thinking-based problem identification and on solving skills. In addition, the teams participate in experiential learning-based practices for enhancing teamwork and communication through prototyping, storytelling and needfinding activities. During the Bootcamp week the first prototypes for the project are created. During the second and third semester the teams participate in weekly seminars where the team's BSc theses are discussed in relation to the project and the scientific perspective required. During the fourth and last quarter, the teams create the final prototype and the final report, which are combined from the individual theses. The students are awarded from 10 to 15 ECTS depending on the challenge and the amount of work done. The bootcamp counts for 2 ECTS, the actual BSc thesis 8 ECTS. In addition there is an option to reward a team with 5 ECTS if the project is exceptionally demanding. For further information on the concept and related research, see the Bootcamp course description in this thesis and in Publication VI.

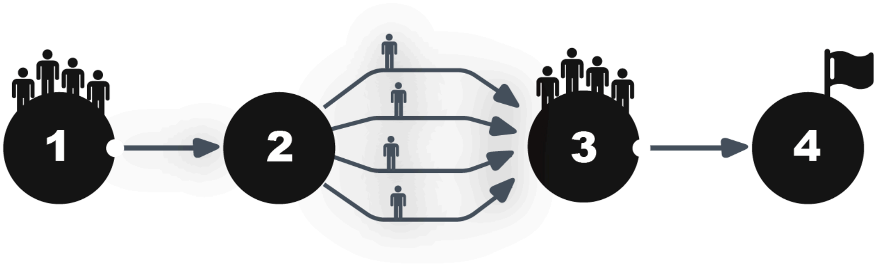

Figure 15. Bachelor level Capstone project starts with a challenge, which is then divided into separate projects. The separate projects are then reconnected into a feasible, viable and desirable solution.

Storytelling and Needfinding, 5 ECTS

> *Storytelling based learning is a novel approach to an entrepreneurial and reflective path, where story is one dimension for the overall teaching approach to create the curriculum, review the readings, structure the exercises and craft the work, provide feedback, leading and coaching, and include the students in the entire developmental process.* (Publication VII, p.7.)

The Storytelling course is based on the *TELL-MAKE-ENGAGE action stories for entrepreneuring* -course developed by the Mechanical Engineering and Design Group and taught at Stanford University, US [78]. In O-CDIO the Storytelling course aims to equip the students with the methods and skills for identifying a story that, in design thinking terminology, would identify a need [31,32], after which, by engaging their audience in an iterative storytelling loop, they would be able to design it to fit the form of a story.

Preliminary ILOs for the Storytelling course are: the ability to identify and model effective personal and team storytelling, to gain interaction design experience, to be able to communicate effectively about real and fictionalized stories, to be able to develop skills required for analyzing diverse and complex problems during and beyond the academy, to qualitatively and quantifiably define engagement by using co-building method, to engage in a team through a shared vision and develop ways to pivot and change, to be able to develop a deeper understanding of others through creative story expression, to be able to design models that inform methods that predict engagement responses to the work, to be able to designing engineering design prototypes that test and validate a story model,and finally to be inspired to pursue life-long learning by approaching storytelling from an analytical and entrepreneurial mindset [7, p. 9-10].

Capstone Bootcamp – introduction to the capstone course, 2-3 ECTS

The Capstone Bootcamp -course is designed to act as an introductory course to the capstone concept as well as the RDC course, though that can be executed as a stand-alone course (see Figure 16). It is aligned with the PDRP course and in essence it is a one-to-three week version of the PDRP course.

Programs	Intended learning outcomes	Assessment
Final presentations for the articles (Monday)	Familiarized with the theories and teaching methods: problem-based learning, learning by doing, design driven learning, challenge driven learning	Peer-to-peer assessment using teaching team approved metrics, team-based grade
Briefing for the week: who am I-my dream-my strategy to make it happen (homework: personality test) (Monday)	learning from our own strengths and weaknesses, getting an idea of what will happen during the week and why. BUT not how - this creates tolerance towards ambiguity	no grading - pass/pass depending on individual - voluntary exercise
Prototyping workshop: egg competition (Tuesday)	Prototyping methods, power of prototyping as a teamwork tool and a way of communicating to different stakeholders	teamwork activity, communication, the actual result from the test, how the "carrier" is designed
Lecture: strategy safari (Tuesday)	idea about management and strategic perspective towards product development and a business perspective to industrial operations	assessment part of the presentations
Workshop: working with Doctor Zou's projects from strategy perspective (Tuesday)	focusing on individual and team presentation skills using management and strategy context	focus on the actual way of presenting = communicating thoughts and ideas to the listeners as an individual and as a part of the team, usage of voice, contact and interaction with audience, stage maner
Team building: rope test for communication (Wednesday)	importance of team building and the difficulty of communicating the right way in a team	commitment to the exercise, feedback and discussion
Capstone project designing experience (Wednesday)	familiarizing with capstone ideology and teaching methods and understanding the importance of real-life learning experiences to ones' career	How well the CDIO loop was understood and implemented, teamwork activities and communication inside and outside the team, planning of time, taking responsibility of the individual and team efforts
Final presentations concerning the Capstone project designing (Thursday)	Seeing a project through, working in a team, achieving a full CDIO loop in a very limited time frame	a test drive of a full project and presentation = pitching your idea to the audience, how well have the different teams efforts being aligned with each other, that is making a concise project co-operation and entity from sub-projects

Figure 16. The program, intended learning outcomes, and assessment for the Bootcamp intensive course. The course was designed to act as an introductory course for design thinking methods and project-oriented and problem-based learning (PBL and POPBL), though it can act as a stand-alone project as well. [149, p.15.]

The Capstone Bootcamp course was initially created to prototype the activating of teaching methods, such as project- and problem-based learning in a team setting, and also design thinking methods. Second, the Capstone Bootcamp course was organized to introduce students to what the capstone projects demand of them and their teams. The schedule for the bootcamp week had several daily routines that consisted of introductory lectures with discussion, prototyping, teamwork, and team building activities throughout the and often late in the evening. All the assignments were assessed during the same day and peer-to-peer feedback and assessment was utilized in addition to the teaching team and outside help. For further reading, see Publication VI in the Appendix.

Radical Design Challenge, 15 to 30 ECTS

The Radical Design Challenge (RDC) is based on several capstone-like courses, which that have active and team oriented project learning embedded into them [12,17-19,20,22]. These are stripped from all procedural forms of teaching and acts as an idea and experience incubator. For example, the RDC course can last from six to twelve months or even eighteen months – if feasible. The challenge, context and content are the metrics that matter.

RDC builds on the vast and established format of capstone courses and focuses mainly on the *observe* and *design* phases of the O-CDIO cycle. The project and the problem-based courses have been around for fifty or sixty years [12]. The Background section introduced the capstone experience as one of the main shifts in engineering education, which was when one of the first capstone-like courses – the Harvey Mudd Design Clinic was introduced:

> *The majority of Capstone courses in engineering context aim to bring the practical side of design and engineering to the curriculum. The goal is to introduce the learning outcomes that are thought important while working in industry. One of the pioneering real-life open-ended Capstone project courses is the Harvey Mudd Design Clinic that started in mid 1960s (12, p.7.)*

Another very famous capstone-like course is the ME 310, which is a Master's level course at the Department of Mechanical Engineering, Stanford University, US. The faculty of ME 310 define the course as a hybrid or cross-over capstone course and a start-up incubator [20].

> *Mechanical Engineering 310 (ME310) is an interdisciplinary, project-based course.. ..and represents a true integration of engineering, business and design disciplines. Originally created at Stanford University, the course has operated continuously for over forty years. Over nine demanding months, students learn*

and apply the Stanford/IDEO design process in product development to prototype, test and iterate to solve real world design challenges for multinational corporate sponsors. Originally created to provide engineering students with real life engineering challenges, the course has shifted from practical engineering experience, to design of mechatronic systems, to design innovation, global collaboration and entrepreneurship. Plus, a high premium is placed on community building and networking amongst ME310 students, alumni and faculty… …ME310 is all hands-on, all the time. Also, each team in ME310 pairs with another team from a foreign university to jointly solve the proposed design challenge. These partnerships add diversity to the project teams and give students the opportunity to experience true international collaboration – an essential skill required in this highly globalized world [43]. (Publication III, p.5-6)

In a typical problem-solving situation there is a prompt that needs to be solved. This includes placing the problem into the form of a solvable task and then implementing it. In the RDC course, the identification of a problem is the first phase in which human-centered based design thinking methods are utilized. The idea is to spend an appropriate amount of time considering the problem space instead of rushing to conceive the solution space. This is easier said than done, since the results – the reflective experience of ideating, designing, and managing the pilot courses, research on similar courses, and the relevant literature – show that students have a tendency to prematurely rush to a solution [5,20].

Focusing on the Observe phase

This section elaborates on the points that emphasize the *Observe* phase in the O-CDIO framework. The aim is shed light on the first phases of the engineering process by going through some fundamentals of the engineering learning process. In essence the argument is that the CDIO framework focuses on creating a sustainable, holistic, even radical and innovative solution to the given problem [e.g 8]. The O-CDIO framework, the main contribution and result of this thesis, sets the main focus on observing and identifying the actual problem. Based on the results presented in this thesis and the clear need for more human-centered approaches to engineering education echoed from the EER literature, the claim is that there is space for more human-centered focus in engineering education [e.g. 2-4, 6]. In practice this manifests in an education process where the focus is shifted from the problem at hand to the individuals and to the team observing, and later solving the problem. Perhaps the best example of this school of thought is the Storytelling-based learning, SBL, method, later presented in this section. In SBL, which is also a novel approach to learning, the philosophy is to focus on the transformative growth of the learner instead of the engineering results that are seen as the product of the students growth process instead of being the end goal [Publication VII, 150]. It is true that this philosophy is well established as an objective, if not thousands then at least a hundred years ago, but what SBL does, it brings it to context of contemporary engineering education [e.g. 1,62,63,150].

The deep learning occurring in a creative problem solving and design process is informal in nature and focuses on the creation, sharing and transmission of explicit and implicit knowledge [151]. A focus on areas such as team composition, team interaction, how to de-structure or structure a design process, as well as what kind of gestures, wording, questions and emotions arise in the process needs to be present. For example, one of the RDC course's, presented in previous section, fundamental aims is to facilitate and promote how the abovementioned processes can be used to enhance the learning process of future designers and product developers [20,27,85]. It is a learning process for the educator as well.

For an engineering and design process to be creative with output ideas that are new and innovative they should have: a suitable physical space, the absence of fixed processes and an embedded institutional practice of letting change happen [20]. Letting change happen is the opposite of trying to make change happen. And, the other way around: in order to make change happen, you have to let it happen. The space for creativity must be optimized whether physical or mental.

All procedural or institutional barriers need to be flexible. Support for divergent, sudden, even unexpected activities needs to be present. This is not merely about tolerating change, it is about promoting and facilitating it in the face of ambiguity and uncertainty [20]. The idea of the RDC course, for example, is to provide a learning experience that promotes: tolerance towards ambiguity, self-discovery, personal growth, engineering working methods and process skills, project management, and the development of group work among other disciplinary and cross-disciplinary goals [Publication III]. To achieve this, all the abovementioned perspectives need to be taken into account.

When working in a group and aiming for radical results, communication is of paramount importance [20]. It is also a very broad, and vague area and difficult to define. In order to communicate efficiently you need to share vocabulary, values, experiences, visions and goals [95,101,152]. The communication situation is like an hourglass and the communication that flows through it depends on the size of the funnel. Thus, no matter how large the other side of the glass is, the amount of understanding that can be achieved is dependent on the diameter of the funnel. This is also one of the main, if not the main, issue in learning enhancement. How to speed up or stimulate the process of transmitting and constructing knowledge? It is considered transmitting when looked at from the outside or from the perspective of the syllabus, but from within the process is about jointly constructing new knowledge [20,153].

According to Leifer and Steinert 2011, design thinking, the prominent human-centered process, school of thought, and method used in the O-CDIO and in the RDC course, integrates problem forming, problem-solving and design [20]. In the O-CDIO context *forming* and *solving* are preceded by an emphasis on the problem *identification* phase though it is conceptually very close to the *forming* phase in the design thinking process [20,30-32]. It is also a human-centered methodology combining engineering sciences with the social sciences, business and design. The most pragmatic manifestation reflecting this is conceptual, rough and rapid prototyping, which also happens to be a process tool. Here the aim of the methods and approach is to create radical innovations, and entrepreneurial thinking in a setting that starts with nothing but uncertainty and ambiguity [20].

When in the identifying phase, the emphasis must be more on finding the right questions instead of finding the answers and making the decisions. It must also be remembered that there is typically an abundance of *right answers* or *feasible design solutions*. Open solution space is of paramount importance to the process, allowing the design team to find their way towards a holistic solution combining complex social, technical and system demands in a dynamic and divergent setting. The aim is to find a viable, feasible, usable, and desirable outcome.

Emphasizing prototyping

One practical manifestation of *Observe* oriented learning and teaching is prototyping. Prototypes are used for exploring ideas and for representing different phases of the evolving design. This is also emphasized by the PDRP - course, which is part of the O-CDIO curriculum. Depending on the system that the prototype is supposed to represent, the building process can be quite difficult since many processes are interactive and formative. Hence, it is imperative to choose the right kind of prototype and the right focus for each phase of the process [21,23,154]. In O-CDIO, prototyping should be about what is being prototyped instead of what it does and what it includes. This will also help to build the right kind of prototypes, which have a clear purpose and are able to communicate that purpose to the user or the customer [23].

Rapid prototyping, especially so that it leaves open space for ideas to grow and develop, accelerates the learning process in a sequential way. Sequential in this context means that as one learning process phase ends with a prototype, another starts after that. Learning is not a linear process, yet the abstraction of the learning sequence helps to understand the role of prototyping and the agile build-to-learn method. The software industry uses a similar protocol. It can be called agile, scrum or lean software development [Publication V]. In O-CDIO and for example in the RDC –course, it is of paramount importance to keep the sequences short enough so that the team or the individual has time to go through the loop several times during the project.

Failing means learning

The importance of failing is another issue and of paramount importance to learning. Winning ideas and insights are often found by failing miserably during the prototyping phase or hitting a boundary of some sort in the early phases of the project. Compared to classical product development, radical innovations need more iteration cycles with divergent and convergent phases [20,155].

In design thinking and, for example, on the RDC course the spiral nature of the process is emphasized by several iteration phases and divergent search activities. In practice, this means continuous design-build-test or do-test-learn cycles, with the focus on the problem rather than the solution. A human–centered approach, with different concept creation phases that also focus on the user and which use truly impactful processes are emphasized here.

It is estimated that the project teams should stay in the early phase of product development and project management for more than a third of the total time [20]. The required tools and processes are very different from the final product development phases where optimization, cost reduction, quality and reliability issues are important [20,155]. In the early phase, concentrating on segments such as needfinding, bodystorming, storytelling, user testing and user experience enactment will help the spanning and understanding of the problem space. The first challenge is discovering the actual needs of the user and making sure who the actual user is. For this to happen the project scope and goal should be broad enough, but without detailed specifications [20].

Storytelling based learning

The storytelling-based learning, SBL, methodology aims to challenge the individual student and team by means of a stimulated reflection process, which results in more effective and higher achieving teams as well as more aware, mindful and holistic engineers. In the engineering curriculum, storytelling-based learning offers a new, interdisciplinary and reflective way to approach and creatively manage the long list of skill-sets required for a holistic and effective engineering education [12,17-19]. Students need socio-reflective skills that engage the individual and the team in a process whereby reflective and socio-reflective consciousness and dialogue-based communication are enhanced through emotions, which function as catalysts to empower the thinking and learning skills of students. In other words, the student learns to see the broader picture with not just the end result but the understanding the growth process leading to it. Below an example how SBL can be used in the class-room with organizing questions that prompt responses through small stories [150]:

Question: Imagine the title, travel back in time story that you tell your 8th grade self.
Short story: Excel at work and ready for transition.

Question; What is the difference in the audience response to the narrative vs. their response to the storytelling?
Short story: Be capable of finding strength in your unique approach and ways of knowing and showing your story.

Question: Where is the heart in your story?
Short story: Develop other than template ways to live, formulate, and tell your story.

Question: Where is the conflict in your story and when did you cause that conflict?
Short story: Seek a strategic understanding of the plot points along the way of your story.

Each question can be prompted in a given session based on the need. For further reading please see Publication VII and [150].

Both SBL and design thinking and are context depended methods, processes, activities and mindsets. Yet the skill to share a story is context-free, it is nothing less than universal combining humans through out history [156,157]. In less sky-touching words there needs to be a sufficient level of knowledge as well as a skill to create and share an engaging story from the chosen context [150]. As mentioned above thee use of the SBL method is context depended. The method and the understanding of it can and need to be context-free. To achieve this goal a deeper level of storytelling skills needs to be achieved. These skills revert to the storyteller and are based on the capability to self-reflect and be mindful. The argument in SBL is that these skills are essential not only for a storyteller but for a practicing engineer as well [150]. SBL sees these *higher order thinking skills* as fundamental to engineers, whom are not only capable of solving engineering problems but solving the right problems in general. This is also the fundamental premise for O-CDIO framework. It is also closely linked to innovation, which by definition needs a holistic approach to happen [30-32]. To end, below an excerpt from the latest research concerning the SBL method by Karanian et al. 2016 [150].

> *In SBL the participants go through a process where they learn to leave space for interactive, continuous and intuitive reflection of the situation. In other words they learn to tolerate ambiguity. This in turn leads to a more authentic and engaging communication. In education and learning outcomes this translates to a more aware and collaborative teamwork. Emotions that are often linked to classroom teaching are boredom and frustration. Motivating the student to pay attention to the topic in hand,*
> *which is being transmitted through a talking head, sometimes referred to as sage on the stage in front of the static and un-flexible classroom, is a fundamental task. Emotions that are related to storytelling are more intensive. In an attempt to engage the audience the student needs to dive into the core of her experiences, dreams, visions and emotions. To reach out and engage she has to grow inwards. This creates suspension and instead of frustration and boredom, the emotions that the student needs to conquer are fear of failure, fear of shame, courage to reach out and courage to be open and sincere. The learning outcome is not only*

knowledge and skills in terms of engaging storytelling and about subjects related to engaging communication and collaboration, but there is also a transformation process where the students learn more about themselves as individuals and as team members. [192, p.10-11].

6 Conclusions and Limitations

University education has many roles. It has to provide the highest possible level of research and teaching, and also educate students to become proactive and contributing members of society. In engineering education, this means the students form the basis of society's and industry's innovation force, whether as product developers, research and development engineers or as entre- and intrapreneurs.

For students, this means in addition to learning disciplinary knowledge, they need to become individuals and team players able to find solutions to complex, and ill-defined problems – global scale grand challenges or incremental contributions to the development of existing systems. In addition, they need to be able to identify latent needs and create products for new markets, innovations if you will, where none existed before. Once this is achieved, they need to be able to execute projects that utilize the opportunities and tackle the challenges arising from them. And they need to be able to do this in a team environment while actively communicating their ideas and thoughts, both inside and outside the team. That is a lot to ask from an engineering student and it is a tall order for the engineering educator.

UTU engineering education undertook a reform process from fall 2011 to fall 2015. The development of engineering education is ongoing but the experiments conducted for this thesis were ideated, designed, implemented and further developed in that timeline. Five different pilot courses were implemented seven different times. The main and underlying idea was to research: ***What strengths does a multidisciplinary university have in terms of engineering education and How can those strengths be utilized in order to educate the engineering students to learn transferable working life skills in addition to the disciplinary knowledge?*** *(See Figure 17).* In addition to the *transferable working life skills* the aspects of *curriculum design* and *teaching methods* were examined. Altogether 11 559 data points were collected and analyzed during the research project.

The final research phase was approached from two perspectives that were formulated to research questions 1 & 2 with a subcategory question for RQ1:

RQ1: How can the CDIO framework be implemented to a Multidisciplinary Science University, covering the whole of engineering education?

RQ2: What activating teaching methods work best in a setting of international and interdisciplinary engineering education?

These questions were a combination of both the structural and content approach to the reform process and to the O-CDIO framework that was induced during the final phase of the research. From the very beginning of the reform process, starting Fall 2011, the hypothesis was that by utilizing the different disciplines of the university to the full the engineering students would firstly gain better understanding about what needs other disciplines have and secondly they would understand their own role as engineers better.

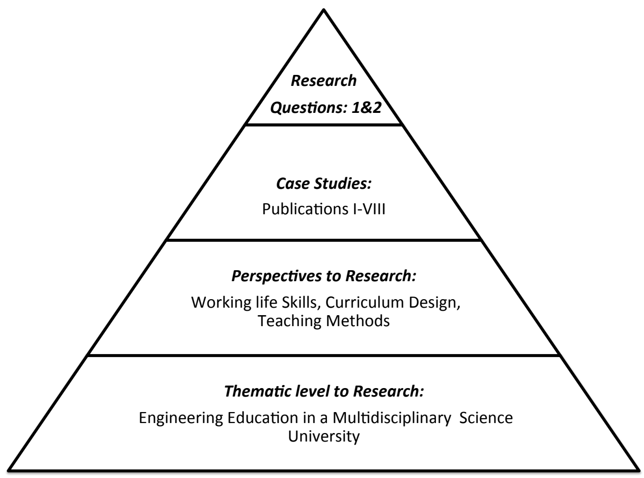

Figure 17. [First presented in the Introduction section]. The first level is the thematic level, which provides the context and the grand theme for the research. The second level are the perspectives through which the research is done and last are the actual research questions that were constructed case-by-case depending on the need and the phase of the reform and development process.

Answering RQ1 the main contribution of this thesis is the O-CDIO engineering education model that resulted from the inductive inference path, based on the results of the experiments. In short the main argument or answer to RQ1 is, yes, it can be implemented by using the O-CDIO engineering education model. The O-CDIO framework is a holistic engineering education model that builds upon an existing engineering education framework. Presented in *Results II* section the emphasis of the O-CDIO model, which is based upon the existing CDIO framework is to focus on the early phases of the engineering lifecycle and to achieve this through the use of human-centered methods, such as the design thinking approach and processes [7,8,30-32]. The reasoning behind the model is that in order to find latent needs and innovative solutions, the problem space needs to be explored rigorously before entering the solutions space. Human-centered based design thinking methods catalyze and facilitate the process of spanning the problem space and designing the required solution, as seen in Figure 19 A&B [20-22,29]. There exists examples of both design thinking applied to capstone and even introductory courses and even to degree level engineering education [e.g.99,158]. The clear majority of these cases are, however, either polytechnic level education or in the cases of research or science universities single courses mostly in the form of capstone- courses. The O-CDIO model is designed to a multidisciplinary science university though it can be implemented elsewhere as well and it covers both BSc and MSc starting from day one to graduation.

The results from the piloted courses were answering the RQ2 for the main part. These results are presented in more detail in section 4, Results II. From the piloted courses and from the present-state-analysis that was collected from the faculty it was learned that human-centered approaches and methods have an effect on skills such as *communication, teamwork, tolerance towards ambiguity and general problem solving skills.* These results are well aligned with current engineering education research discourse and the literature related to engineering education and its teaching methods. However, the research conducted with the storytelling-based learning has showed how powerful a socio-cognitive method with affective level learning outcomes can be and how difficult it is in practice to implement. The main new result was how the teaching methods used in the PDRP course stimulated teamwork, which was found to be both rewarding and the main source of learning (see Publication VIII and the Results I section). Many studies indicate that teamwork is often seen as a major contributor to learning but at the same time one of its main constraints [Publication IV,2,22]. Despite that, the findings of the piloted courses were well-aligned with those of similar studies [2,6,16,17,20,21]. From this perspective the answer to RQ2 is dual. First, the activating and experiential teaching methods such as are used in the CDIO framework work well yet there is a demand for affective level learning outcomes even though they are hard to assess.

The O-CDIO Framework Knitting the Experiments into a Single Model

The inductive analysis that led to the creation of the O-CDIO model is dealt with in the Research Methods section, and the actual model is presented in Results II. In this section we will present only a summary of the model

The O-CDIO model sets its emphasis on the early phases of the engineering lifecycle. Instead of focusing on finding a solution to the given problem the *Observe* part of O-CDIO focuses on understanding and, if needed, spanning the problem space. The rationale being that, in addition to being problem solvers, engineers also need to become problem identifiers. In other words, engineers need to be able to solve the right problems – in addition to solving them well. Both the CDIO- and the O-CDIO model aim for radical technical innovations. The difference comes from the emphasis on early phase problem identification. In practice this means that a Capstone course for example can use up to 30-40% of time allocated to the course for problem identification.

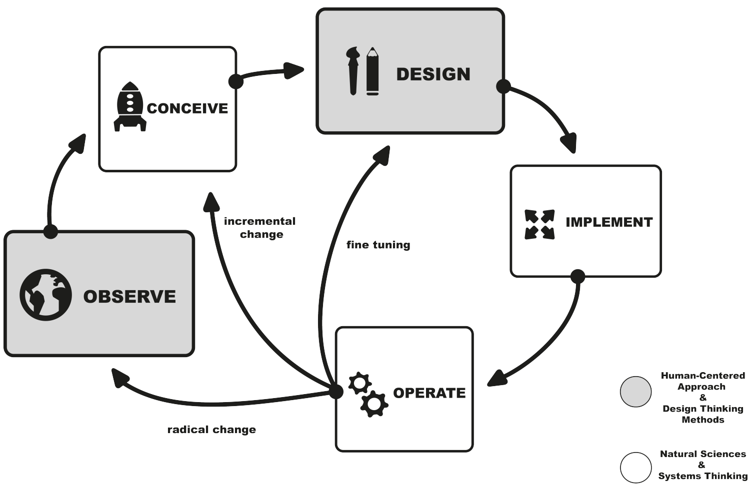

Figure 18. [First presented in the Results I section]. The O-CDIO engineering lifecycle is based on the CDIO lifecycle, which is also the foundation that the O-CDIO model builds upon [7,8]. In essence the O-CDIO framework and the human-centered thinking behind it emphasizes the need to thoroughly investigate

and observe the whole problem space before entering the solution space. This is done using human-centered design thinking methods including: Needfinding, Storytelling, Observing and Rapid Prototyping. After the problem space is identified we can move to the solution space where the best-suited solution can be ***conceived****. The next phase where design thinking methods are applied is the* ***design*** *phase where the conceived solution space and solution is designed into pragmatic artefacts, services or solutions. Prototyping, Needfinding and Storytelling are once again the tools used. The human-centered design thinking methods are derived from several different disciplines, such as anthropology, social psychology, the arts in general, and history; in engineering terms, anything that works in the given situation and challenge.*

Engineering and engineering education do not exist without the intention to serve a cause. This requires that any tools can be used and made available in order to achieve something. Mathematics or philosophy can exist for the sake of mathematics or philosophy. They do not need to explain themselves. Engineering, however, needs to always have an intention and a real-life surface boundary. This also authorizes it to use any means necessary to achieve these goals. Whether using natural sciences or human-centered sciences.

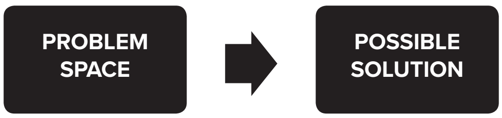

Figure 19 A,

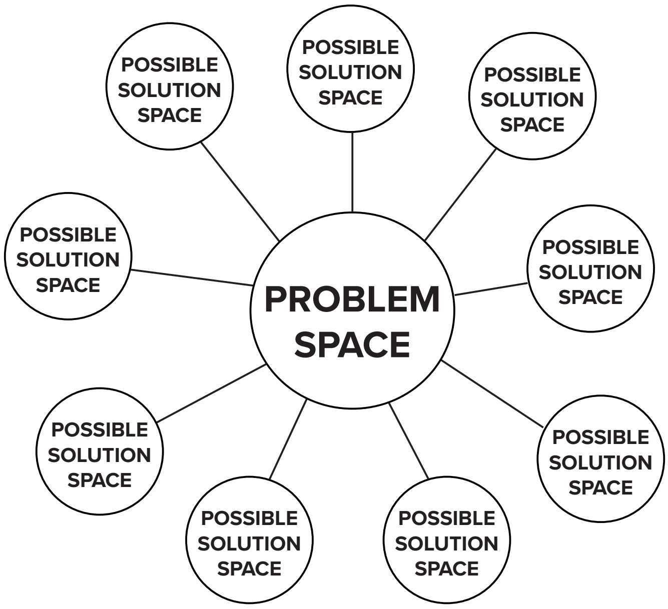

Figure 19 B.

Figure 19 A&B. Direct problem solving (above) versus the O-CDIO approach to problem solving. Typically, engineering problem solving is done by using deductive methods and the natural sciences as the foundation. It is widely used and taught and it is very important for engineers. It is, however, not enough if radical innovations and new unexplored boundaries need to be discovered and crossed. This is what the O-CDIO approach (below) focuses on by when it uses design thinking methods. First the whole problem space needs to be understood and crossed – if needed. The result can be that the problem is only partly technical or it can be something totally different. After discovering the boundaries of the problem space using design thinking methods, the team can move to the solution space where a feasible, desirable, usable and viable solution to the challenge can be designed.

How to implement O-CDIO

The O-CDIO model was developed to answer to many of the needs identified by the previous research, the EE research literature, and the results of the piloted prototype courses in UTU's engineering education reform [2,3,5,6,8,17-19,21]. Though O-CDIO was a hypothetical model, evidence from similar studies showed that there was not only a need but also the possibility to implement the model [6,18,163].

The O-CDIO models pedagogical foundation and philosophical stance requires it to be constantly reiterated, redefined and redesigned by its users. It is meant to be an everlasting work-in-progress model tied to its context wherever implemented [6,18,163]. The detailed and contextual design of the model, curriculum and courses require a participatory approach from the faculty for them to commit to the process and adapt to the methods and goals of their specific context. There is a plethora of questions to be addressed that this study does not take into account. For example: What metrics influence the creation of a new kind of learning and how should they be assessed? How should students, educators and universities be correctly rewarded and by whom? How can educational change be managed when it typically takes from five to fifteen years to show reliable results, and even then the evidence is interpretative? [4,8,14,18,61]. Also, how do we measure success in engineering education if it takes from ten to fifteen years for us to know if our graduates were successful in their professional lives? Even then, it is safe to say that there are other factors influencing their professional success than just their participation on the EE degree courses. All of these questions remain interesting challenges for future research. This thesis does not shed light on what it takes to make that change happen or what is required for an institution to implement the O-CDIO model, it aims to share results of the prototyped courses and the present-state-analysis and introduce the O-CDIO model and the reasoning behind it. The work towards developing a more detailed model and course descriptions with teaching methods continues. Whatever the outcome, the most important question remains: *How can we make change occur*? However, this thesis considers the question: *How can we develop engineering education in a more student-centered direction*? to be far more important than the model itself. Though metrics (commitment, levels, resources, skills, knowledge) and shared implications with adequate levels of abstraction can be found, every development process is, by default, unique. Thus, it is argued that there is no universal *How?* that would work from A to Z in any context. Thus, why not educate, experiment, engineer?

Structure of the Research

This chapter presents the limitations of the research and the results and then the possible future paths for research. The limitations of the research will focus on the construct of the research, internal and external limitations, and on the causal and correlation links as well as the generalizability of the research. In addition, the fundamental philosophy of the approach and the final goal of the model and this thesis. This research was based on both a pragmatic approach as well as a social constructivist research approach [46,87], with the pragmatic approach being more prevalent. The actual research was conducted using a MM approach with. The use of MM added value to the reform of the degree program and the understanding of the research project. In brief, quantitative research was used to build the basis and understand the boundaries of the phenomena studied, while qualitative analysis was used to understand the qualities of the phenomena [46]. Social constructivist theory on the other hand was the predominant philosophy of the research in the sense that it focuses on the researched object, in this case, the student. This study was based on the social constructivist theory of learning and behavior, and it utilized the pragmatic approach of research with the mixed methods approach [46,118,123,128,133,134,137,159,160]. The above approach was adopted because the aim was to achieve pragmatic results. Unlike the world of mathematics or physics, human relationships and communities and societies have peculiarities that make an objective approach impossible [46,55]. This means that the qualitative researcher needs to look into institutions, social structures and frameworks, conventions and practices produced by people, not by laws of nature. These phenomena, such as hierarchies, language, conflicts and decisions influence humans and transform their behavior. There is no deductive logic that covers the phenomena. Instead, a researcher can look for causal descriptions that can explain the social mechanisms, processes and structures that occur [46,55].

An approach that focuses on qualitative research methods and inductive analysis means that the premises of rigorousness in the research and transparency of the results are achieved by the thorough use of well-established research methods and a transparent and well-documented research process. Mainly because the results are always interpretations of what was researched, there is no universal or absolute truth in them. What the researcher needs to do instead is to transparently show what was done, how it was done and the interpretations the approach created. This ensures that anyone interested can use the same documentation and methods to see where the path leads. This might be a different interpretation, which then gives space for scientific discussion and further development.

Internal and external limitations

The main caveat of the research results is the link between the researched pilot courses and the actual O-CDIO model. The experiments that were conducted during the research provided valuable feedback and results, which were gained from the learning outcomes and the analysis of the teaching methods of the prototyped courses. Due to the use of an action research setting, it was possible for the courses to be developed according to the results gained from previous research. In essence the research results from the piloted courses did not reveal any new groundbreaking results. However, they were very much aligned with the literature and the results from similar studies.

The main result of this thesis, the O-CDIO model, was crafted after trying to understand what implications the results of the piloted courses have for the broader picture of engineering education and how can they be utilized within degrees, universities or systems levels in general. There are several similar spaces or systems operational already [6,102-104,161]. The question was how to achieve the required basis for future education within the setting of a typical multidisciplinary university. A typical university is formed around disciplinary boundaries, has constraints on the staff due to the fact that they divide their time between disciplinary research and teaching, has the possibility of an in-house approach to interdisciplinary courses and projects, has limited financial and educational resources, and finally has the aim of serving local needs for skilled labor, in addition to national and international roles and needs.

The outline is broad and the reality is always context driven but the constraints offer a perspective for viewing the presumptions and premises of the O-CDIO model.

The results and findings from the present-state-analysis as well as from the piloted courses were well aligned with the literature and the scientific discourse concerning both issues [2,14,20,21]. This makes the generalizing of these results feasible as well.

The O-CDIO model, on the other hand, is designed based on results and experiences from a multidisciplinary science university. It is for other resaech together with future research to prove how well the model fits, for example, a university of applied science or a university of technology [99-101]. The O-CDIO model is and needs to be context driven. It cannot be copy-pasted to any institution but instead it has to be tailored to meet the specific requirements concerning the goals set by the institution and its constraints concerning the staff, structure, methods and content that are prevalent in that particular environment. Another important aspect is that the working culture of the location is of paramount importance but a national culture and world trends will also affect the study environment as well [6,23,95]. This research project did not take these perspectives into account in any way. To summarize, the O-CDIO model can be implemented within various environments much like the CDIO framework that the O-CDIO model is based on. Second, the implementation process must always be context driven and context specific.

Reliability and transparency

The transparency of the research, its different phases, research settings and the documentation and amount of the data coupled with the use of common methods of analysis establish the main source of reliability for this study. The research was conducted mainly by using qualitative methods, while the research objects were mainly humans and their actions. Even when quantitative methods were used, people were the research objects. This means that the causal links between cause and effect and the reasoning behind some of the correlations are based on interpretation. In the majority of cases the analysis was conducted within a team setting and mainly by the author, who is also solely responsible for the results presented in this thesis. This means that the data are not researcher specific and neither are the methods, although the O-CDIO model that the research produced and the reasoning of the causality of the results are researcher dependent.

One of the main challenges for a researcher is drawing theoretical conclusions from empirical data so that it is both credible and understandable. In the case of inductive reasoning this is particularly challenging as it is, by its very nature, always incomplete. Ketokivi & Mantere 2010 present two strategies to induce conclusions. These are idealization and contextualization. The understanding of the difference between the strategies can produce better argumentation, which results in the improved evaluation of the data and the research results [55]. Since qualitative research methods are the main approach in this study, these strategies are briefly presented below.

Ketokivi and Mantere, have identified at least five challenges in positioning and sharing one's own scientific research with the science community [55]. These include the abundance of different theories and paradigms, the difficulty of positioning the research regarding a broader theoretical discourse while demonstrating a contribution to the discourse, epistemological incommensurability, a lack of standards for especially qualitative research, and finally the complexity of having a social negotiation process with all the possible stakeholders.

All claims that are based on empirical data have at their foundation some variant of inductive reasoning. The problem arises with the unresolved issues surrounding the credibility and quality of the justifications produced by the inductive reasoning. This issue remains unresolved in contemporary epistemology. Consequently, it has led to a ***practical reasoning dilemma***, whereby researchers attempt to convince their audience with scientific argumentation based on a variety of grounds and claims. There are no accepted principles and methods for governing the practical reasoning method and process. It is not the complexity of the process that creates bias but the nature of inductive reasoning, which is incomplete due to its very definition. There is bias and confusion, even disagreement, not only between the research traditions but also within the theoretical discourses and paradigms. However, by understanding the logic behind the different reasoning and approaches, a researcher can be more consistent and transparent with his research. Also, in the scientific community, the difference between policy and methodology can be recognized, and even renegotiated if needed.

The Future of Engineering Education

Engineering education is developing as the world develops and there is a clear working vision what EE must achieve in order to serve the needs of industry and society in a sustainable way [e.g. 2,3,13,24,77,84,143,152]. There is a plethora of learning methods and several EE frameworks and models, the majority of them start with the premise of seeing the individual learner as an active reasoner [e.g. 7,8, 62-64, 90,95,141,152,153,162]. All this means that the key question to be asked is not whether students need to learn relevant and transferable working life skills. The question is how to achieve the intended learning outcomes. This research sets out how to facilitate and stimulate learning in the context of engineering and the environment of a multidisciplinary science university [27]. The research included a present-state-analysis of education reform in an EE university degree program and the results from several different piloted courses related to that reform. The results showed that by using activating teaching methods students learn relevant skills, such as: problem solving, communication and teamwork. The O-CDIO model created by the degree program and the preliminary courses takes into account the need for such courses throughout the degree and not just at the beginning and end [12,17-19]. The main aim of the model is, however, to educate students to become skillful *problem definers* in addition to *problem solvers*. This is facilitated by the use of human-centered, design thinking methods, such as storytelling, needfinding and prototyping in a real-life product development context that continues throughout a whole project cycle. When the focus is on finding latent and yet-to-be discovered needs and markets, there is a possibility to achieve radical, disruptive and holistic solutions instead of linear and incremental solutions. The O-CDIO model is very much a work-in-progress model and it is up to future research to show how it can be demonstrated as a whole.

At the quantum level of engineering there are few certainties, continuity or laws of nature that can be followed. Engineering education and research must adopt methods and approaches, vocabularies, even values from the social sciences and use both quantitative and qualitative methods to discover answers to *what* and *why*, and especially *how*.

Whenever there is a statistical representation of a *typical* or *statistical engineer* there is also a caveat looming to deceive and mislead the reader, whether a policymaker or an educator [2,147]. All students are individual and their demographic and socio-economic backgrounds and past experiences influence them and their learning. Thus, there are thousands of styles of learning [93]. The level of abstraction is important for creating an adequate level for policymaking, for example, but it should not be expected to explain the more detailed nuances of the actual learning process, nor should it steer university, faculty or department level change and the development process.
Learning is socially constructed and that means that the conceived truth is dependent on the previous ´truths´ of the individual and the context where new knowledge is accommodated or assimilated. Individual perception and the reception of the truth varies depending on the individual. The world makes sense, but we are also make sense of the world [123,133,134,139,140]. Engineering students have both intrinsic and extrinsic reasons for studying engineering [164]. The intrinsic reasons are values for their own sake while extrinsic reasons need to have an outcome. Intrinsic reasons could be, for example, an altruistic motivation to save the planet, to help those in need, to make things, or they could be extrinsic, such as having a good career or obeying the will of one's parents. Although parents and teachers may have a role to play in a student's choices, the overall motivation is derived from the self. Gender, race, and socio-economic status influence these issues [2,164]. More importantly motivational issues are rarely explicit, consciously thought through or well defined. In sum, to successfully graduate as an engineer, a student must develop the identity of an engineer. In the building process it is important that the student understands the big picture of engineering. In order to do that, active learning, project-based learning and design experiences offer a valuable tool [2]. This is also one of the foundational objectives of the O-CDIO model, and its human-centered, teaching method and toolkit.

It is to be hoped that the O-CDIO framework will answer the need for integrated D-I and especially O-D-I (see Figure 14) experiences throughout a degree program – not just in the beginning and at the end of the studies [6,12,16,135]. The results of the piloted prototype courses show that: *tolerance of ambiguity, the engagement of different teaching methods, course structure, an understanding of problem, project-based learning methods, design thinking practices, understanding the role of teamwork and communication, and even excelling and appreciating learning* are all increased and enhanced through teamwork. All this gives impetus to more experimentation and the further development of the framework. Finally, and most importantly the main goal for creating a model that adds human-centered methods to the engineering curriculum is to add to the discussion and development of pragmatic hands-on tools so that faculty and faculty leadership are able to create engineering education that is student-centered.

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169. **Sonja Leskinen**, m-Equine: IS Support for the Horse Industry
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