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Identification of Sustainability's Threshold Concept(s) Among Multi-Discipline Engineering Students

A thesis

submitted in fulfillment

of the requirements for the degree

of

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at

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by

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*"Mō tātou te Taiao ko te Atawhai
"Mō tātou te Taiao ko te Oranga"*

It is for us to care for the environment to ensure its well-being. In doing so we ensure our own well-being and that of future generations.

Te Kete Ipurangi

Sustainability and the protection of the environment are important values in Māori culture and are reflected in traditional Māori practices such as kaitiakitanga (guardianship) and rāhui (temporary resource protection). These practices involve taking a long-term perspective and considering the impact of actions on the environment and future generations.

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Abstract

This mixed-methods study investigated and validated the sustainability threshold concept among multi-disciplinary engineering students, taking into account students' perceptions and the impact of the sustainability threshold concept on student understanding of sustainability in their respective disciplines, while employing the constructivism paradigm. Sustainability education faces numerous obstacles, and under these conditions, some disciplines struggle to connect sustainability to their field. This study utilised threshold concept theory and liminality to develop a new model to help connect students' perception, liminality, sustainability, and key competencies in sustainability education.

Three years of data collection in the midst of pandemic led to the development of a questionnaire for 100 students enrolled in a multidisciplinary sustainability course. In addition, a total of 25 participants were interviewed across a variety of disciplines. Findings indicate that there is a correlation between student perceptions and learning about sustainability; more advanced students (fourth-year) viewed sustainability as less relevant than novice students (first-year).

Through the development of a novel model based on the threshold concept, this study contributes to a better understanding of students' perceptions and experiences of sustainability education. This study sheds light on both the opportunities and challenges of teaching sustainability in engineering education. It also emphasises the importance of students' perspectives in learning about sustainability.

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Acronyms

CE Civil Engineering.

CHE Chemical Engineering.

EE Environmental Engineering.

EEE Electrical and Electronic Engineering.

EIA Environmental Impact Assessment.

EU European Union.

FE Fire Engineering.

FTA Fault tree analysis.

ICT Information and Communications Technology.

ISO International Organization for Standardization.

LCA Life Cycle Assessment.

LCI Life Cycle Inventory.

LCIA Life Cycle Impact Assessment.

LCT Life Cycle Thinking.

ME Mechanical Engineering.

MECHA Mechatronics Engineering.

MPE Materials and Processing Engineering.

NFR Non-functional Requirement.

RoHS Restriction of Hazardous Substances.

SDGs Sustainable Development Goals.

SE Software Engineering.

SETAC Society of Environmental Toxicology and Chemistry.

TC Threshold Concept.

TCT Threshold Concept Theory.

UN United Nations.

UNCHE United Nations Conference on the Human Environment.

UNEP United Nations Environment Programme.

UNESCO United Nations Educational, Scientific and Cultural Organization.

WEEE Waste Electronic and Electrical Equipment.

Glossary

Algorithm in mathematics and computer science is a finite sequence of rigorous instructions, typically used to solve a class of specific problems or to perform a computation. Algorithms are used as specifications for performing calculations and data processing. SE participants in this study used [algorithm](#) to refer to their coding and problem solving skills.

Antithesis is used in writing or speech to contrast with or reverse a previously mentioned statement, or when two opposites are introduced together for contrasting effect.

Boolean Logic is a form of algebra which is centered around three simple words known as Boolean Operators: “Or,” “And,” and “Not”. They are widely used in electrical and electronics engineering, and also sometimes used to perform [fault tree analysis](#).

Bounded in this study refers to one of the [Threshold Concept Theory](#) characteristics. It can be explained as: clear demarcation that a concept resides within one discipline and not another.

Concept is defined in this study as an abstract idea. Concepts are understood to be the fundamental building blocks of principles, thoughts and beliefs.

Fault tree analysis is a type of failure analysis in which an undesired state of a system is examined.

Life Cycle Impact Assessment is the part of a life cycle assessment where the elementary flows (environmental resources and releases) gathered in the life cycle inventory are analysed to determine the probable environmental consequences of the project.

Life Cycle Inventory is one of the life cycle assessment methods that entails recording a product system’s inputs and outputs.

Non-Functional Requirement in the context of systems engineering and requirements engineering is a requirement that specifies criteria that can be used to judge the operation of a system, rather than specific behaviours.

Oxymoron is a figure of speech that juxtaposes concepts with opposing meanings within a word or phrase in a way that creates an ostensible self-contradiction.

Paper/course used interchangeably in this study and it refers to a sequence of lessons or a study plan on a certain subject, generally culminating in a test or certification.

Patch / software patch is a short-term fix for a piece of programming intended to address security vulnerabilities, enhance functionality, or introduce new features.

Troublesomeness is one of the [Threshold Concept Theory](#) characteristics; in this study the term mainly refers to challenges that students faced, and it can also be interpreted as a difficulty that causes inconvenience.

This is dedicated to Dr Fariba Mostafa, my mother, whose encouragement and faith in me enabled me to embark on this journey. Her motivation, hard work and emphasis on the importance of education as a prerequisite for achieving success in life made everything possible.

Chapter 1

Introduction

1.1 Chapter Overview

The introductory chapter establishes the context for the study by outlining the motivations for the research topic. The first section of the chapter discusses the researcher's reasons and rationale. Following that, the relevance of the research is explained, as are the research questions, the researcher's interest in doing the study, and an overview of the research strategy. Finally, the chapter concludes with a summary of the thesis.

1.2 Justification and Significance of Research

The exploitation of nature for personal gain has had severe consequences, which have been examined from political, ethical, moral, and intellectual perspectives in light of several emerging issues such as climate change, increased freshwater demand, poverty, carbon emissions, and hyper-consumerism. These issues have the potential to devastate our planet and have led to the advocacy of sustainability, which aims to achieve economic development while protecting the environment and promoting social responsibility. Engineers, as the primary implementers of socioeconomic growth, have a significant role to play in addressing these global challenges. To do so, engineering curricula must include a robust sustainability paradigm. This context has led to the growth in popularity

of sustainable engineering, which represents a conceptual shift away from traditional engineering practices by expanding the problem and solution domains of engineering to include the economic, social, and environmental sustainability pillars (Allenby et al., 2009; Marjoram et al., 2010).

This research is significant because it addresses the need for a comprehensive study on sustainability education in engineering. Teaching students about sustainability in engineering is a continuous conceptual and practical challenge. Students must examine their position in society and the impact of their actions on the environment (Allenby et al., 2009; Sharma et al., 2017; Zwickle et al., 2014). Establishing an appropriate curriculum that incorporates sustainability themes requires both students and instructors to undergo a "paradigm shift" (Mulder, 2017; Rampasso et al., 2018). However, sustainability is a broad and nebulous concept, making it difficult to determine which subjects to include in a course that will benefit diverse engineering disciplines (Sharma et al., 2017; Zhan et al., 2015).

Integrating skills and experience from other disciplines to teach sustainable engineering is a challenge for many educators (Shephard, 2008). Furthermore, most universities and colleges have comprehensive, authorized engineering curricula with little room for sustainability, making it difficult to add or enhance courses without significant curriculum revisions (Björnberg et al., 2015; Sharma et al., 2017). Sustainability education is multidisciplinary in nature, as it involves three dimensions: social; economic; and environmental. These dimensions bring together people from different disciplines to work towards solving a common problem (Jensenius, 2012). However, one challenge in multidisciplinary sustainable engineering papers is the interdisciplinary content and structure of the sustainable engineering course (Sharma et al., 2017). Finding the right balance between environmental protection, social justice, and economic development can be difficult in sustainability education for engineering students (Levintova and Mueller, 2015).

Under these circumstances, some engineering disciplines struggle to connect sustainability to their curriculum. The difficulty in conveying and teaching sustainability in engineering is not accidental. Sustainability is a complex topic and its boundaries exceed the standard engineering education (Sharma et al., 2017; Zhan et al., 2015). Therefore, it is essential to ensure that critical aspects are

not overlooked and that students can connect with and apply sustainability concepts within their disciplines.

The purpose of this research was to use Threshold Concept Theory (TCT) in order to bring about the ontological and conceptual alterations in engineering practice necessary to achieve strong sustainability. Harlow et al. (2011) argues that TCT is more than a basic building block; it is a self-contained framework geared towards discipline-specific comprehension. Acquiring TCT necessitates ontological and conceptual transformations, as it introduces a new way of thinking to the learner that was previously unavailable (Cousin, 2006; Harlow et al., 2012; Peter et al., 2014; Scott et al., 2012).

This framework makes it possible to reform sustainability structures from a mixture of multidisciplinary and interdisciplinary to transdisciplinary approaches. Where an interdisciplinary approach integrates knowledge from different disciplines, in transdisciplinary work, the normal boundaries between disciplines are broken (Jensenius, 2012). Transdisciplinary research uses a holistic approach, crossing the limits of predefined knowledge areas and creating a unity of frameworks beyond the traditional disciplinary perspective (Guerra, 2017; Rampasso et al., 2018; Shields et al., 2014). To restructure sustainability into a transdisciplinary approach, the TCT could be used to identify the main points of sustainability in engineering.

The findings from this study could assist curriculum and program developers in understanding the concepts necessary to include in sustainable engineering courses. The novel framework introduced in this study also has the potential to provide a foundation for future work by establishing a tool for understanding the needs of engineering students, not only in sustainability education, but also in other areas.

The purpose of this research was to use TCT to bring about the necessary ontological and conceptual alterations in engineering practice in order to achieve strong sustainability. By applying TCT to sustainable engineering education, we can ensure that critical aspects are not overlooked and that students can connect with and apply sustainability concepts within their disciplines. Through this approach, we can effectively bridge the gap between traditional engineering practices and the emerging field of sustainable engineering.

1.3 Statement of Research Questions

The study's goals are guided by the following set of research questions, whose answers are provided in Chapter 6.

Main question: How do student perspectives on sustainability influence students' understanding of threshold concepts in sustainability engineering education?

Supporting question:

- What are the threshold concepts in sustainability for engineering disciplines?
- Are threshold concepts in sustainable engineering common across disciplines?
- How do students perceive sustainability?

1.4 Motivation for this Study

When I think about my own pursuit of sustainability, I remind myself that my opinions are mostly based on my own life experience, my capacity to understand the world at large. I acknowledge that I may not be privy to all of the complexities and nuances of global sustainability, but I'm committed to learning more and adjusting my approach based on what I learn.

I have been consistently confronted with the concept of sustainability as an engineer, and I have noticed that this subject often causes confusion among engineering students. In order to help my peers better understand and apply sustainability in their profession, I decided to research the threshold concept(s) of sustainability in engineering. Through my previous research in fields such as solar energy, I have observed that many engineering students struggle with the concept of sustainability, which is now a multifaceted idea encompassing economic, social, political, and environmental dimensions.

There are several challenges in teaching sustainability to engineering students from various disciplines. The concepts, techniques, tools, and paradigms of

sustainability are not well-defined within engineering education, and the current definition of sustainability has flaws that need to be addressed in the curriculum. It is therefore important to find new ways to engage engineering students in the exploration of the fundamentals of sustainability and threshold concepts within sustainable engineering. These students will be the future leaders responsible for creating a sustainable future, so it is crucial that they have a strong understanding of these concepts (Cristina, 2016; Björnberg et al., 2015; Mulder, 2017; Rosano, 2018; Shields et al., 2014; Thürer et al., 2018).

The purpose of this study was to see how successfully students' perceptions of sustainability may impact their comprehension of TCT in engineering disciplines. To involve engineering students in learning the basics of sustainability and TCT within sustainable engineering, a new strategy was required. This study aimed to provide a building block for a better understanding of engineering student perceptions of sustainability, as well as a necessary framework to incorporate a needed strategy for change.

1.5 Overview of the Research Design

This study used an interpretivist paradigm to understand and characterise students' perspectives and experiences with sustainability. Considering the research's goals and objectives, phenomenography was used to create the study, which was produced in three phases, each with its own set of stages and tactics. Figure 3.1 depicts an overview of the research design.

1.6 Overview of the Thesis

The rest of this chapter describes the research process and procedures and includes a variety of research strategies. It is comprised of seven further chapters, as outlined below.

Chapter 1

The [introduction](#) is a concise synopsis of the research and thesis document.

Chapter 2

The [literature review](#) is presented in Chapter 2, and covers the relevant aspects of the following areas: sustainability; threshold concepts; key competencies; and life cycle assessment. The chapter opens with the literature on how to define sustainability and presents a brief but comprehensive history of sustainability education. This section concludes with further information on sustainability and engineering education. Threshold concept theory, including its general definition and characteristics, shapes the second section. The chapter ends with a discussion of life cycle assessment.

Chapter 3

The [theoretical framework and methodology](#) for this study are discussed in this chapter. Additionally, this chapter describes the methods and processes utilised to collect and analyse data. The chapter ends with an overview of the frameworks defined and employed in the following chapter's discussion.

Chapter 4

Chapter four represents the analysis of the [data](#) from Phases One to Three. Instead of separate chapters to cover each Phase of data, findings were simplified and reduced to one chapter. Furthermore, since this study uses phenomenography, all findings shared across multiple Phases are treated as one. In 2019, I conducted the first phase of the study, which consisted of a group interview with 18 participants from different disciplines and a questionnaire filled out by 98 respondents. Phase Two involves document analysis by five students. Phase three entails an in-depth interview with five participants from various fields and one lecturer. All the findings were combined; Table [3.3](#) presents the names which were used to represent participants' findings.

Chapter 5

[This chapter](#) synthesises the results and literature in order to develop and understand how students' perceptions could help with identifying threshold concepts in sustainably engineered systems. This chapter is organised around key themes found in [Chapter 4](#). The new model developed for the threshold concept liminality is also discussed, with examples.

Chapter 6

[The concluding chapter](#) is presented with each research question answered. The final section of the chapter addresses limitations and strengths of the study, implications, and recommendations for future research.

Chapter 2

Literature review

2.1 Chapter Overview

This research required an in-depth focus on the two primary areas of sustainability and [Threshold Concept Theory \(TCT\)](#). The purpose of this chapter is to provide an analysis and critique of the existing literature in the aforementioned domains. Nonetheless, the broad scope of sustainability made things more challenging than anticipated. The lack of literature on sustainability and [TCT](#) added to the already complex nature of this research. As a result, one solution was to broaden the scope of the literature to include topics like [learning competences](#) in sustainability and [life cycle assessment \(LCA\)](#).

This chapter is broken down into four sections. The first section, named [sustainability](#), discusses the definition of [sustainability](#), [sustainability education](#), [challenges associated with sustainability in engineering education](#), and finally, the role of [engineering in sustainability](#). The key premise of the sustainability section is that incorporating sustainability into engineering curricula is controversial, yet essential. This section also serves as a basic problem and solution phase, with a critical review of relevant literature.

The [second section](#) is divided into three subsections which present the theoretical frameworks that guided this research. The first two sections cover the fundamentals of [TCT](#) and [liminality](#). The final subsection summarises the literature on [threshold concepts and sustainability](#). While some of the authors discuss

similar themes to my research, they do not significantly overlap my findings or the scope of this study.

The [third section](#) developed in response to the complexity and breadth of sustainability education. [Key competencies](#) were a common key word in the literature on sustainability education, and I was interested in evaluating these models because of their unique connection with the [TCT](#). Although there are many competencies models, I opted to concentrate solely on the fundamentals of competencies. My focus was to gain an understanding of the basic principles and develop a strong foundation in these competencies.

Finally, [LCA](#) is discussed, both because it had a significant impact on my findings and because it is used as an educational standard for sustainability in engineering education. Here, the information evaluated is deliberately selective to keep the discussion directly relevant to my research. This section contains a subsection on the history of [LCA](#) and its application in engineering education. It explains the [LCA framework](#) so that any reader who is unfamiliar with the term can refer to this chapter for more information.

The majority of the literature cited here was discovered by using search keywords in Google Scholar or the University of Waikato library. The key words were kept concise in order to produce a focused, targeted literature review. While I made every effort to maintain the literature up to date with newer journal papers, there were a few exceptions, such as the paper being too significant or there being no other option.

2.2 Sustainability

The development of sustainability as the ultimate global issue of the twenty-first century did not arise in a vacuum. Sustainability recognises the critical role of education, which was preceded by a strong campaign that peaked in the 1990s (UNESCO, 1992). An explanation of sustainability is provided here, along with an emphasis on the importance of ongoing education and research in this field. The purpose of education for sustainable development and examples of sustainable education are discussed. The section then critiques the resulting structure, providing a basis for assessing sustainability education in engineering. This section discusses sustainable engineering as a departure from conventional engineering and the normative methods, tools, and frameworks that have traditionally been used in the discipline.

2.2.1 Sustainability Education Declarations

The development and current status of sustainability education can only be understood through an examination of its past. The role of sustainability education as a necessary means to inculcate the idea of sustainability in the world was first provided by the [United Nations Conference on the Human Environment \(UNCHE\)](#), also known as the Stockholm Declaration, in 1972 (Table 2.1). While the conference was not entirely focused on higher education, the conclusion of the declaration was to call on UNESCO to address sustainability challenges and to protect and improve the environment by including environmental education from primary school to university (Lozano et al., 2013; Michelsen et al., 2015; Wright, 2002; 2005).

Since the Stockholm Declaration, there have been multiple conferences and declarations aiming to include sustainability in education and to seek help from universities in doing this. Environmental education was the initial catalyst for sustainability in higher education, which paved the way for sustainable development (e.g. the Stockholm Declaration, the Belgrade Charter, the Tbilisi Declaration, and the Brundtland Report). The world's first formal initiative for environmental education was started by the Tbilisi Declaration. The Tbilisi Conference was held in 1977 after a call from university heads at the Stockholm Declaration from UNESCO. As a result, it became one of the most critical moments in the history

of international sustainability education declarations. The declaration focused on environmental sustainability and asked all university heads to support the inclusion of environmental studies in their internal and external resources for all people (Lozano et al., 2013; Wright, 2002; 2005).

The primary objectives of environmental sustainability were to educate the public about the interconnectedness of the environment and humanity, foster the adoption of pro-environmental mindsets, train people to recognise and address environmental problems, and encourage a general shift towards more eco-friendly lifestyles (Michelsen et al., 2015). Environmental sustainability terminology gradually changed to sustainable development, and sustainability was introduced in much more detail than before (Aikens et al., 2016).

The complexity of sustainability, as the concept exists now, was not always present; it was slowly built upon over the years. The starting point of the revolution for sustainability was in 1987 with the Brundtland Report. The report is also known as *Our Common Future*, presented by Gro Harlem Brundtland. A new approach to environmental unification was offered in the Brundtland Report, and the term “environmental sustainability” was replaced with “sustainable development” (Lozano et al., 2013; UNESCO, 1987).

UNESCO (1987) introduced sustainable development as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The sustainable development terminology was replaced with environmental sustainability, and the context of sustainability changed from focusing heavily on environmental factors, to being defined by the three main pillars of sustainability: environment; economy; and society.

For the Brundtland Report’s vision of sustainable development to become a reality, significant societal shifts and new ways of thinking, as well as new government policies, were required. The required shift in perspective was achieved with the help of education and by reorienting fundamental beliefs to bring about new thought processes. The educational system required a holistic approach to manage such a rapid transformation. Thus, nearly 30 years after the declaration have been dedicated solely to sustainability education, with the role of education in this endeavour being spelt out in detail in Agenda 21 (Michelsen et al., 2015).

Agenda 21 is the outcome of the Rio de Janeiro Earth Summit in 1992, also known as The United Nation Conference on Environment and Development. This is a 351-page document divided into 40 chapters that have different sections covering most of the topics related to sustainable development, oriented to a distant dream of achieving sustainable development by the year 2000. Most of the chapters are focused on environmental sustainability; however, Chapter 36 discusses education in detail and how it is essential in achieving a sustainable society (Wright, 2002).

'Education is critical for promoting sustainable development and improving the capacity of the people to address environment and development issues' (UNESCO, 1992, p. 320)

Two themes are common across all of the declarations as illustrated in Table 2.1. The first is universities' moral obligation not only to teach but also act as sustainable institutes. The second is the need to expand and educate the public about the challenges we are facing as a small community from a global perspective. Wright (2005) suggests partnerships with government and non-government organisations, as they are essential for the growth of other sectors. In this sense, universities serve as both the initial and ultimate stages of a generational preparation process. Every single proclamation echoes the increasing trend that universities may become ideal role models through teaching sustainability (COPERNICUS, 1994).

Among other themes found by Wright (2005) and Lozano et al. (2013), developing interdisciplinary content and ecological literacy hold the highest importance from my point of view. Wright (2005) suggests that ecological literacy "is the ability of an individual to comprehend the functions of the world with a realization that all human activities have consequences for the biosphere and the translation of this understanding into action for the health of the earth". An awareness of students' own activities and decision making will have an impact on their behaviour. There are a few ways to achieve this outcome in the classroom using project-based learning and case studies. Lozano et al. (2013) have updated a few of Wright's (2005) themes. Among these updates, "ecological literacy" has been changed to "curricula"; however, there is not a good explanation as to why this change has been made. While "ecological literacy" is not exactly easy to understand, "curricula" is not very different.

Developing disciplinary content is necessary, as students will not be able to transform their belief systems overnight by taking mandatory courses (Lozano et al., 2013). The content must be polished and presented to them throughout their degree. The shift in paradigm needed cannot be achieved instantaneously, but rather over some period of time (Wright, 2005). Most of the declarations invite everyone to become more environmentally friendly and motivate universities to achieve these goals. Meanwhile, there has not been any real guideline as to how these ideas should be delivered to students (Wright, 2005).

Ultimately, sustainability education must provide a way for everyone to transform their way of thinking and their perception of the world. A better way of thinking critically is needed so that people can find their way around a complex system. Each action and behaviour will affect how students get to their final decisions. The utilization of systems thinking coupled with a refined and comprehensive approach to teaching sustainability would equip the education system with the necessary advantage to attain a competitive edge (Michelsen et al., 2015).

The evolution of sustainability education language from 1975 to 2013 is mapped out by Michelsen et al. (2015) through a systematic review of the relevant literature, which shows sustainability has been linked to “environmental education” in the past, especially before 1990. The Brundtland report is credited with solidifying the popular acceptance of sustainable development ideas, which had not been widely disseminated in publications throughout the 1980s (UNESCO, 1987). The term “sustainability” only became popular around 2005 due to United Nations Decade of Education for Sustainable Development. Michelsen et al. (2015) suggest that sustainability has been through three primary stages, namely:

- Orientation and experimental wave (before 1990)
- Transition and development wave (1990–2000)
- Expansionary wave (after 2000)

The UNESCO (1987) report first proposed the concept of sustainable development in the “transition and development wave”. The “orientation and experimental” wave addressed only environmental issues. The expansionary wave began in 2002 after the World Summit on Sustainable Development in Johannesburg.

It was then that sustainable development and lifelong learning to achieve sustainability were introduced. Universities' involvement was also strengthened, as education began to be included as an integral component of sustainability (Michelsen et al., 2015). Table 2.1 offers a quick summary of the declarations on sustainability education throughout the years. Each row provides the year and topic of the event, as well as a short synopsis of each to help in understanding them better. As Table 2.1 demonstrates, the focus on sustainability fluctuates substantially as the years go by, and the general focus on sustainability shifts from concentrating heavily on the environment to holistic thinking and a greater emphasis on education.

This section summarised the transition from environmental education to sustainable development and provided a short synopsis of the history of sustainable development. The emergence of sustainable development as a field of study and practice was based on a better understanding of how human activities can permanently harm natural systems, as well as a growing awareness of the interdependence of social and ecological factors. The section that follows discusses how this awareness arose, as well as how sustainable development frameworks can be used to better understand the differences between the challenges we face.

Table 2.1*Summary of declarations on sustainability education throughout the years*

Declaration/charter/program	Year	Theme/idea	Description	Challenges
Stockholm conference / Declaration of the United Nations Conference on the Human Environment (UNESCO, 1973)	1972	Environmental education	The conference invites governments and peoples to use common aims for the protection and development of the human environment, for the benefit of all	Environment; Society
Belgrade Charter (Michelsen et al., 2015)	1975	Environmental issues worldwide; environmental education	The goal is to form a world population that is conscious and concerned about the environment and its associated problems. A global community with the knowledge, skills, attitudes, motives, and dedication to work individually/collectively toward solutions of current problems and the prevention of new ones	Environment
Tbilisi declaration (Scott, 2016; UNESCO, 1977)	1977	Environmental education	The world's first intergovernmental conference on environmental education. A declaration to guide the development of the field of environmental education and to create new patterns of behaviour of individuals, groups and society as a whole towards the environment using awareness, knowledge, attitudes, skills, participation	Environment
Brundtland report (UNESCO, 1987)	1987	Sustainable development; Environmental education	A new strategy, commonly known as sustainable development, to unify the environment and development was introduced by Gro Harlem Brundtland	Environment; Society
Talloires declaration (Purdy, 2013)	1990	Ethical obligation; Environmental literacy; Higher education for sustainability	The Talloires Declaration was the first official dedication to environmental sustainability in higher education to be created and signed by university officials. It is a ten-point action plan for including sustainability and environmental literacy in teaching, research, operations and outreach at colleges and universities	Environment; Sustainability; Society
Conference on University Action for Sustainable Development/Halifax declaration (International Association of Universities, 1992)	1991	Ethical obligation; Socioeconomic sustainability; Partnership; Leadership; Higher education for sustainability	A declaration which acknowledged the leadership role universities could play in addressing the environmental disaster. An action plan to enable universities to restructure their environmental policy, practice, and curriculum so that everyone could contribute to environmental sustainability on local and global levels	Environment; Sustainability; Society
Agenda 21 (UNESCO, 1992)	1992	Ethical obligation; Socioeconomic sustainability; Partnership; Higher education for sustainability	Agenda 21 is the outcome of Rio de Janeiro Earth Summit, a 351-page document divided into 40 chapters that have different sections. It covers most of the topics. A far reaching dream of achieving sustainable development by the year 2000; since then it has been changed to 2030. Every country was advised to draw and follow their local agenda 21	Environment; Sustainability; Society
Kyoto declaration (International Association of Universities, 1993)	1993	Ethical obligation; Sustainability action plan; Higher education for sustainability	Urged the universities to give a more precise explanation of sustainable development and to respect ethical obligations. It also encourages the world to reduce greenhouse gas emissions and to invite countries to take part in reducing the onset of global warming	Environment; Sustainability
Swansea declaration (Harper, 2013)	1993	Ethical obligation; Higher education for sustainability; curriculum	The Swansea Declaration was part of the higher education community's move to recognize and deal with the problem of impact on the environment. It was also a warning due to the poor higher education representation of sustainable development and Agenda 21	Environment; Sustainability
COPERNICUS charter (COPERNICUS, 1994)	1994	Sustainable development; embedding environment and sustainability across higher education	The COPERNICUS Charter first recognises the urgent need for humanity to shift to more sustainable fashions. It was intended to stir university progress around environmental sustainability in Europe. Charter leaves room for interpretation with no strict rule and regulation	Environment; Sustainability
World declaration for higher education (UNESCO, 1998)	1998	Ethical obligation; Higher education for sustainability	Education is a must for human rights, democracy, sustainable development and peace, and should be accessible to all at any stage of their life, no discrimination on the grounds of race, gender, language, religion or economic, cultural or social distinctions, or physical disabilities. Principle introduced could be used for higher education institutes regardless of their national and regional situations	Environment; Sustainability;
Lüneburg declaration (Schroth et al., 2013)	2001	Role of universities; Curriculum reorientation; Ethical obligation	The Lüneburg declaration focused on the importance of continually reviewing and updating the sustainability knowledge in institutions of higher education. It also emphasizes on using both theoretical and practical ways to support sustainability education	Sustainability

Ubuntu declaration (Michelsen et al., 2015)	2002	Curricular change; Learning for sustainability	An initiative that focuses on enhancing science and technology education to promote sustainable development	Sustainability
Johannesburg declaration (Tokuç, 2013)	2002	Education for sustainable development; UN decade of EDS	The Johannesburg Declaration builds on earlier declarations since 1992 while reminding all nations to practise sustainable development and multilateralism as a path forward. The declaration is an agreement to focus mainly on the prevailing conditions that pose severe threats to the sustainable development of people	Sustainability
Graz declaration (UNESCO and Association, 2005)	2005	Curricular change; Sustainability models; embedding sustainability across higher education	Coincident with the beginning of the United Nations Decade of Education for Sustainable Development in higher education, the Graz declaration emphasises the commitment of universities to sustainable development and cooperation of universities and society	Sustainability
Sapporo declaration (UNESCO, 2008)	2008	Need for sustainability; Curricular change; Sustainability models	The Sapporo declaration (the world's first G8 university summit) states universities' responsibility as the main driving force for promoting a sustainable society. The particular responsibilities and action needed to achieve this was discussed	Sustainability
Bonn declaration (UNESCO et al., 2009)	2009	Education for Sustainable Development	The Bonn declaration reminded everyone that education is a significant factor in improving well-being of the human. After decades of progress, we have the knowledge and experience available to improve education for sustainability	Sustainability
Turin declaration (Sylvestre et al., 2013)	2009	Holism; Sustainability model; Education for Sustainable Development	The Declaration indicates that sustainability science plays an essential role in the most significant challenges that humankind faces. Universities should promote sustainable development at the local level and global level through new approaches within the educational and research systems	Sustainability
World Conference on Higher Education (Michelsen et al., 2015)	2009	Holism; Lifelong learning; Moral obligation; Education for Sustainable Development	WCHE provided the key stakeholders in higher education, national policymakers, and institutional leaders an opportunity to put into action the universal obligation and ambition to make higher education sustainable development ready for the second decade of the twenty-first century. More than 1,400 participants from nearly 150 countries and territories took part in the 2009 WCHE	Sustainability
Abuja declaration (Lozano et al., 2013; Michelsen et al., 2015)	2009	Transdisciplinary; Top-down approach; Partnerships	The Declaration acknowledged the sustainability problems in the African continent and the role of higher education in educating the leaders and educators of tomorrow. A particular focus on the crucial importance of inter-institutional collaboration is placed	Sustainability
The future we want Rio/ Rio+20 Treaty	2012	Education transformation; Top-down approach; Partnerships; Lifelong learning; Sustainability models; Curricular change	The treaty recognises the effort that has been put to embed sustainability within higher education, while acknowledging the urgency to rethink higher education and its role to transit toward a sustainable future	Sustainability
Transforming our World: The 2030 Agenda (Johnston, 2016)	2015	Lifelong learning; responsibility of universities; transformation research	A global plan by the United Nations to pursue 17 sustainable development goals, also known as a radical plan for a better future. They have emphasised a need for a better education and the inclusion of sustainability in higher education again	Sustainability

2.2.2 Sustainability and Sustainable Development

Some people, according to [Bell \(2011\)](#), believe that the phrase “sustainable development” is contradictory because modernisation and industrialisation, which have historically been the fundamental drivers of growth, have necessitated the exploitation of natural resources and environmental destruction. Others regard sustainable development as the greening of industrialisation. The concept of sustainable development aims to make both the economic system, and the environmental systems that support it, sustainable ([Lozano et al., 2015](#)). As a result, they believe that including the environment in industrialisation and development as we know it can lead to sustainable development ([Bell, 2011](#)). In this regard, the maintenance of human welfare is an inherent component of sustainable development.

The discussion of sustainable development and the role of engineers requires an understanding of the primary challenges it aims to solve ([Bell, 2011](#)). Unfortunately these challenges are monumental: millions of people still lack access to fundamentals like clean water, proper healthcare, and quality education, despite widespread international efforts to improve these conditions ([Tejedor et al., 2018](#); [Sharma et al., 2017](#); [Rosano, 2018](#); [Olsen et al., 2018](#)).

Environmental effects is a multifaceted issue, and it is also a concern for the future of humanity ([Boca and Saraçlı, 2019](#)). Overpopulation and increased consumption are endangering the environment’s ability to provide essential services such as clean air and water, as well as a stable climate suitable for modern living ([Boyle et al., 2004](#)). We are depleting potentially renewable resources such as water, wood, and food faster than the earth can replenish them, endangering these life-sustaining systems. Without considering future demands, the use of non-renewable resources such as oil and minerals threatens to bring economic and social structures to a halt.

The harvest, processing, and use of natural resources causes direct damage and contamination to ecosystems, impairing their ability to function. While the consequences for humans, both now and in the future, are significant and critical, the loss of natural places is a moral problem in and of itself. Concerns about broad devastation of natural systems in order to support increasing consumption rates and material standards of living cannot always be answered. Modern

sustainability rhetoric arises from decades of environmental issues arising from human civilisations' effects (Bell, 2011).

Fisher and McAdams (2015) argue that environmentalism has made a huge stride in public awareness as a social, ethical, and political movement. In the view of some, environmentalism is the latest in a series of movements formed to combat the abuses of industry on the natural world (Bell, 2011; Boyle et al., 2004). A major watershed in the history of contemporary ecology occurred when Rachel Carson published her book *Silent Spring* in 1962. After publishing her book, which described the lethal consequences of unchecked resource use, the public understanding of these dangers continued to grow. As environmental pressure groups have come together throughout the world, governments across the globe have been compelled to treat environmental concerns seriously (Carson, 1962).

Neo-Malthusian thinkers, most notably Paul Ehrlich and Garrett Hardin, provided the basis for today's environmental movement. During the Industrial Revolution, English economist Thomas Malthus noted that a rapidly growing population may end in famine and the collapse of civilisation. Malthus failed to account for agricultural modernisation, which increased agricultural productivity faster than he anticipated, averting the catastrophic food shortages and social collapse that he had previously predicted. At this point, scientists were afraid that population growth would outstrip the capacity of natural and industrial systems to deliver necessary resources, culminating in global hunger and ecological and societal collapse (Bell, 2011).

According to Paul Ehrlich, exponential population increase would overwhelm agricultural output, resulting in starvation and the breakdown of natural systems. He advocated for strong population control methods that would forcefully limit fertility and population increase (Bell, 2011; Creech, 2012). Despite several critiques, neo-Malthusians remain insightful in their analysis of population increase and its consequences. Many religious organisations have criticised promoting birth control, notably abortion, as a way of controlling reproduction. The strategy was criticised for its one-sided approach of evaluating just population expansion in underdeveloped nations, without taking into consideration the environmental consequences of increased consumption by more wealthy populations. In other cases, neo-Malthusian forecasts were too pessimistic and some of their recommended solutions unpleasant (Bell, 2011).

In the 1970s, environmental campaigning remained focused on issues of population growth and resource use. The 1972 *The Limits to Growth* was based on computer modelling of resources and pollution under various population and consumption growth scenarios (Meadows et al., 1972). While some of the more dramatic forecasts of ecological collapse and resource over-extraction did not materialise, other trends in resource use and pollution are worse than anticipated (Meadows et al., 2002). *The Limits to Growth* posed a challenge to unrestricted economic growth, all the more so given the strong link between economic activity and resource exploitation (Bell, 2011). *The Limits to Growth* proposed a state of equilibrium or an economic system that achieves a “steady state” as a viable solution (Bell, 2011). The idea of a steady-state society or economy has been entrenched in modern environmental debates.

Through conflict and trade-offs between environmental preservation, economic progress, and fulfilling the needs of the world’s poorest people, sustainable development arose. At its most basic level, the concept of sustainable development is a compromise that preserves prevailing patterns of growth while emphasising environmental concerns; at its most extreme level, it offers a fundamentally new approach to economics, development, and human connections with the natural world (Baker, 2006; Neumayer, 2013). International organisations have formalised sustainable development through talks, with the United Nations playing a prominent role through a number of significant conferences, conventions, and commissions. A short summary of major conferences and reports held during the last 45 years is provided in the [declaration section](#).

While sustainability should be our primary objective, achieving it in a short period of time is very difficult (Sharma et al., 2014). Sustainable development is often used interchangeably with sustainability in the majority of political, economic, and educational documents. There is a subtle recognition that the problem of sustainable development is everyone’s duty - a concept hinted at in the Brundtland Report, *Our Common Future*. The Brundtland Report defined sustainable development as a development that meets current needs without compromising future generations’ ability to meet their own (UNESCO, 1987).

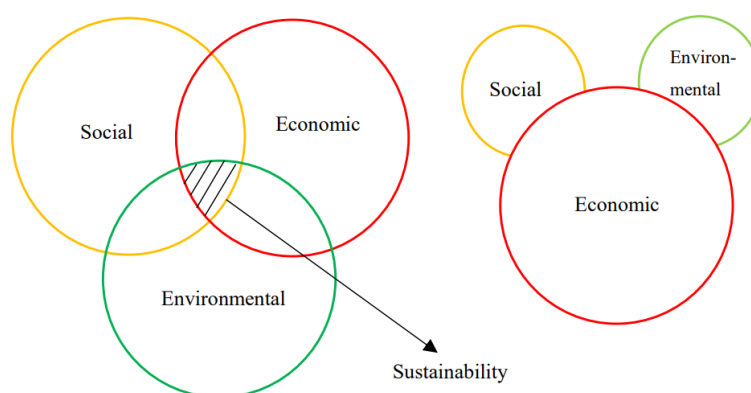
This notion has received majority appreciation, as well as condemnation from a minority. Many regard the Brundtland concept as an important component in developing a comprehensive understanding of the global sustainability crisis (Mebratu, 1998). Some critics believe that the term’s meaning is so amorphous that

virtually anything might be used under sustainability criteria (Kelly-Quattrocchi et al., 2016). Even if these observations are true, the Brundtland definition is still the platform on which all sustainability and sustainable development talks have been built (Carew and Mitchell, 2002).

Sustainable development is typically represented by a Venn diagram (Figure 2.1) which depicts three circles (environment, society, and economy) as being in an overlapping relationship. Every circle in the three-layered design represents a facet of sustainability. The three sustainability pillars are symbolised by the identical-sized circles. Generally speaking, sustainable growth is achieved by balancing the three main pillars of the economy, society, and the environment (Lozano et al., 2015; Loringa, 2020).

Figure 2.1

Conceptual illustrations of sustainable development adapted from Lozano (2008) and Sustainable Aotearoa New Zealand (2009)



Regrettably, the triple bottom line is no longer viable. Gerland et al. (2014) encouraged all to abandon the notion of exchanging the three interdependent dimensions. Instead he recognised that the Earth is a closed ecosystem, and that humanity's choices have an effect on it. To address the challenges posed by a rapidly changing world, we must consider alternative models of development. While human footprints should be minimised, the Earth's limited resources and natural space must be shared fairly. While sustainable development is critical, the conventional "triple bottom line" model with distinct social, ecological, and economic pillars (Figure 2.1) is incapable of addressing the Anthropocene's problems (Hauschild et al., 2017; Rockström et al., 2015).

We require an integrated strategy that re-establishes the link between human advancement and the ecosystem (Figure 2.2). It requires a paradigm shift in which the economy is viewed as a means of achieving societal goals and creating wealth within the Earth's boundaries. To achieve a more sustainable and balanced global economy, governments, corporations, individuals, and institutions must work collaboratively. All policymaking must include a transition to a steady-state economy with constant energy and material flows. New, comprehensive forms of development do not preclude expansion in certain sectors, but rather necessitate the transition to a new, stable, and resilient ecosystem (Hauschild et al., 2017; Rockström et al., 2015).

As obvious as this may seem, sustainability encompasses much more than Brundtland's straightforward description; sustainability must be viewed holistically, as a closed system comprised of several subsystems that must be considered at all times. Sustainability has been defined as a highly precise situation in which the requirements of both humans and environment are met. By contrast, sustainable development is a strategy aimed at achieving sustainability (Hector et al., 2014; Lozano, 2008). Thakran (2015) compares sustainable development to a paradigm that enables us to envision a future that is balanced in terms of environmental, social, and economic dimensions.

Figure 2.2

Strong sustainability model adapted from Rockström et al. (2015)

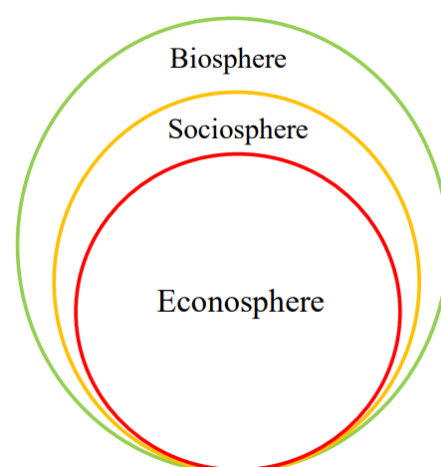


Figure note: This is the updated version of the triple bottom line of sustainability model. Biosphere represents the environment, Sociosphere represents the society, and Econosphere represents the economy.

Open and closed control systems can be used to view this from an engineering perspective. An open-loop control system, or non-feedback system, is one in which the output has no effect on the control process's input. A closed-loop or feedback control system is a type of control system that uses an open-loop as its forward path, but incorporates one or more feedback loops between the output and the input. While an open-loop control system may accomplish the task, a closed-loop system with feedback is considerably superior. Sustainability is the feedback loop that identifies current mistakes and may aid in resolving problems associated with sustainable development goals. In 1987, the Brundtland Report, with its creative title *Our Common Future*, reminded everyone that all sustainability issues are global in scope and that it is up to everyone to take responsibility for them. During the first wave of sustainability ([the orientation and experimental wave](#)), concern for the environment was growing due to concerns about human well-being and the scarcity of limited resources.

Regardless of how this framework is referred to or explored, it is crucial to understand that achieving sustainability often entails understanding the critical role of ecological, social, and economic variables in deciding a development's success. These aspects are evaluated concurrently as a starting point, and compromises are acknowledged. As awareness of sustainability develops, possibilities emerge for merging these three distinct sectors of concern in search of synergy and mutual benefit.

Sustainability entails respecting ecological constraints on the growth of human demand for resources and the capacity of the environment to absorb pollution, recognising the importance of development in delivering improved quality of life, particularly to the world's poorest, and recognising the critical role of local communities and individual citizens in achieving and maintaining change. The following section discusses how the inclusion of all these responsibilities in engineering education is not simple. The difficulties that exist in teaching sustainability to engineers lie in the complexity of issues, the range of disciplines that must be integrated, and the limited opportunities for practice and implementation.

2.2.3 Difficulties with the Inclusion of Sustainability

Education policy and curriculum should be designed with sustainability in mind; the [declarations](#) can serve as a roadmap for incorporating sustainability into higher education, since they give clear principles to follow ([Rampasso et al., 2018; 2019](#)). As previously mentioned in the [sustainability declaration](#) section, the need to include sustainability in the engineering curriculum has become more pertinent as the focus of the declarations has shifted from being purely environmental, to also covering social and economic aspects.

[Rampasso et al. \(2018\)](#) stated that the transition away from environmental toward social and economic concerns is significantly more difficult for engineers since it demands the introduction of “engineering responsibilities.” Although desired, many educational institutions have not incorporated the idea of “engineering responsibilities” ([Mulder, 2017](#)). Engineers are being held accountable for the unfavourable social and environmental effects of their solutions. Engineers find this change tough because it requires a change in their perspective on the world and how they approach problem-solving ([Rampasso et al., 2018](#)).

Although challenging, changing the engineering curriculum is necessary. A paradigm shift is necessary, despite sustainability’s ambiguity and complexity, since it might be difficult to decide which subjects should be included in a course to best serve a variety of engineering specialisations ([Sharma et al., 2017; Zhan et al., 2015](#)). Nevertheless, engineers must consider the impact of their actions on social and environmental components and not only on economic aspects. Sustainability needs to be incorporated into engineering curricula in order to bring about the required paradigm shift ([Mulder, 2017; Rampasso et al., 2018](#)).

Therefore, many institutions require substantial effort to enhance their curriculum, even if there are no set guidelines for how sustainability should be integrated into higher education ([Rampasso et al., 2018](#)). Consequently, sustainability and engineering education face a number of challenges. Specifically, sustainability is a multifaceted concept that has evolved to encompass economic, social, political, and environmental dimensions, all of which have an impact on engineering education (Section [2.2.2](#)). Within engineering education, sustainability ideas, techniques, tools, and paradigms are not well defined for each engineering field. Additionally, the current definition of sustainability has flaws and

should be revised and updated in the current curriculum (Cristina, 2016; Björnberg et al., 2015; Mulder, 2017; Rosano, 2018; Shields et al., 2014; Thüerer et al., 2018).

Effectively teaching students about sustainability in engineering is a continuous conceptual and practical challenge (Allenby et al., 2009). Students must examine their position in society and the influence of their activities on the environment (Sharma et al., 2017; Zwickle et al., 2014). Additionally, imparting information regarding sustainability in engineering to a diverse set of students is difficult (Sharma et al., 2017). As a result, most teachers struggle with integrating skills and experience from several disciplines in order to teach sustainable engineering (Rampasso et al., 2018). Moreover, because the majority of universities currently have comprehensive and authorised engineering curricula with no space for sustainability, it is hard to add or enhance courses without significant curriculum revisions (Björnberg et al., 2015).

Another barrier to sustainability inclusion in higher education is the multidisciplinary and interdisciplinarity of higher education, both of which are typically incompatible with sustainability education. Multidisciplinary is a process in which a problem is divided into various components and people from diverse fields collaborate to solve it, each with a particular focus. Interdisciplinarity seeks a holistic approach, one that transcends the boundaries of domains of knowledge, allowing for complete integration of disparate concepts. Interdisciplinarity is a process in which individuals from disparate fields collaborate to generate new knowledge that does not fit neatly into any of the original fields (Rampasso et al., 2018; Shields et al., 2014).

The three components of sustainable development - social, economic, and environmental - make it a multidisciplinary endeavour. These elements provide a multidisciplinary feel to sustainability, as individuals from many disciplines collaborate to tackle a shared problem (Jensenius, 2012). According to Rampasso et al. (2018), the technical components of a particular engineering discipline are typically heavily stressed in engineering courses. As a result, among engineering students, there is often an incorrect emphasis on environmental preservation, social justice, and economic development, or a lack of a consistent balance between these three dimensions of sustainability (Levintova and Mueller, 2015). Some disciplines of engineering have therefore treated sustainability as unrelated to their disciplines (Biswas, 2012). Universities must plan, coordinate, and

design new courses with input from all experienced lecturers to mitigate this problem, which is by itself a challenge given the economic context for current university policies ([Rampasso et al., 2018](#)).

Another noteworthy problem with incorporating sustainability principles into higher education for engineering students is engineering students' lack of interest in sustainability topics. As previously noted, this apathy might itself be the outcome of imbalanced course design. If there is a disconnect between students' perceptions of their field and principles of sustainability, they may become bored and tired with the topic ([Biswas, 2012](#); [Sivapalan et al., 2016](#)).

According to [Nowotny et al. \(2018\)](#), another challenge associated with implementing an interdisciplinary sustainability course is a shortage of conventional and relevant content that covers the wide definition of sustainability. Additionally, because sustainability is a multidisciplinary concept whose content is updated on a regular basis, the engineering curriculum material becomes obsolete ([Rampasso et al., 2018](#)). In these circumstances, some engineering disciplines perceive sustainability to have no practical relevance to their study. For example, despite the fact that software engineering is a part of engineering, software engineers sometimes struggle to connect their expertise to the concept of sustainability taught in multidisciplinary classrooms ([Palacin-Silva et al., 2018](#)).

The importance of incorporating sustainability into higher education, and particularly engineering curricula, has grown. However, due to the complexity and ambiguity of sustainability, the lack of guidelines for its integration, and the difficulties in teaching it to a diverse group of engineering students, this transition is difficult. There are also barriers such as imbalanced course content and a lack of interest among engineering students, as well as issues with the way that higher education's multidisciplinary and interdisciplinary nature interacts with sustainability concepts. A paradigm shift in the engineering curriculum is required to overcome these obstacles through the coordination and design of new courses with input from all experienced lecturers. In the next section, the role of engineers in sustainable development is analysed. The role of engineers is defined, and a range of possible definitions for sustainable engineering education are outlined.

2.2.4 Engineering and Sustainability Education

Engineering is one of the first professions associated with the development, acquisition, and application of three key fields of technology, science, and mathematics in order to comprehend, design, develop, and produce outcomes using materials, equipment, tools, and systems for a specific aim (Marjoram et al., 2010). To put it differently, engineers are creators, designers, innovators, and most importantly practitioners who are able to shape their thought by use of scientific and mathematical concepts for applications such as the design, manufacturing, and operation of products and processes while accounting for limits set by economics, the environment and other sociological variables (Mina, 2013; Rosen, 2012).

Environmental, economic, and social constraints have created a complicated relationship with engineers. As a result, engineers have served as a link between real-world applications and science. Engineers employ science and technological practices to produce technologies, which are then used to fulfil societal needs by exploiting natural resources. On one hand, the complicated interaction of the engineers makes them the prime target, depending on your point view, for defending/destroying the planet. On the other hand, they are helping society to live better and progress (Marjoram et al., 2010).

Engineers use resources to drive economic activity. Resources utilised in engineering come from the environment, and waste from engineering processes is discharged into the environment. The services offered by engineers promote societal harmony and culture (Rosen, 2012). Given the close connections between engineering and core aspects of human life, it should be no surprise that attaining sustainability in engineering is essential to achieving a better future (Kreith, 2012). Because of higher education's role in helping students acquire sustainable ideals and abilities, higher education has been held up as a model for educating future students and contributing to the growth of science and technology for everyone's benefit (Cristina, 2016; Björnberg et al., 2015; Mulder, 2017; Rosano, 2018; Shields et al., 2014; Thüerer et al., 2018). Yet, as discussed above, incorporating sustainability into the curriculum in a way that permits a paradigm shift to transform the students' ideals is not without its problems (Rampasso et al., 2018). However, institutions must continue to teach the next generation

of engineers to strive for sustainable growth ([Rampasso et al., 2019](#); [Sharma et al., 2017](#)).

Students must be self-motivated in order to participate in sustainability initiatives, as internal motivation pushes students forward in their studies. In some aspects, their interest in the topic is motivated by their own goals and self-perceived motivation. According to [McCormick et al. \(2015\)](#) it is impossible to ensure that students will learn if they are just given information without any assistance in their cognitive growth. Because of higher education's role in helping students acquire sustainable ideals and abilities, higher education has been held up as a model for educating future students and contributing to the growth of science and technology for everyone's benefit ([Cristina, 2016](#); [Björnberg et al., 2015](#); [Mulder, 2017](#); [Rosano, 2018](#); [Shields et al., 2014](#); [Thürer et al., 2018](#)).

According to [Wilson \(2019\)](#), engineering students are more likely to have a feeling of personal responsibility for addressing science and technology-related sustainability concerns. Nevertheless, [Wilson's \(2019\)](#) results show that the merging of engineering education and sustainability education is relatively uncommon, and that educators should take advantage of these students' natural motivation to study more about science and technology. Discovering the sustainability challenge for which students feel the most personal responsibility is vital to creating a bridge between any engineering discipline and sustainability education because, without the will to learn and grasp the benefits of a sense of personal responsibility, there is no incentive for students to act. Since both professional and personal responsibility impact each other ([Wilson, 2019](#)), engineers are most likely to do good for the community if they feel both personally and professionally responsible.

It is essential to listen to what students have to say about "sustainability" and "sustainable development" in order to have a complete comprehension of what sustainability entails. According to [Fisher and McAdams \(2015\)](#), students' perspectives on sustainability determine what they consider to be the source of a problem, who or what they hold responsible for taking action, and the kind of solutions they feel are required to address these challenges.

[Björnberg et al. \(2015\)](#) observed that just one student in their study referred to the Brundtland report, and the rest of the participants associated sustainability with "system thinking" and "future thinking." It is not novel to connect system

thinking to sustainability for engineers. As [Rampasso et al. \(2019\)](#) noted, future engineers will have a direct impact on society and environment, so it is essential to integrate system thinking in engineering education. Other authors have also addressed the holistic and systematic components of sustainability, finding that the transdisciplinary character of sustainability necessitates teaching it using system thinking by default ([Björnberg et al., 2015](#); [Zeegers and Clark, 2014](#); [Fisher and McAdams, 2015](#)).

The relevance of students comprehending their decisions' influence on the environment and social issues has been examined throughout the years. As an illustration, [Kumar et al. \(2005\)](#) and [Ramanujan et al. \(2019\)](#) pointed out the necessity for mechanical engineers to think about the social, environmental, and economic implications of their decisions, in addition to the technical ones. As [Tejedor et al. \(2018\)](#) points out, the integration of sustainability into engineering education necessitates both systemic thinking and transdisciplinarity. It's important to understand how students think about sustainability and what motivates them to learn more about it. What students perceive to be the notion of sustainability will carry over to their decision-making, and inform their judgments about the credibility and validity of what they have learnt in their specific discipline ([McCormick et al., 2015](#)). Student perceptions can even hinder the discovery of fresh and creative solutions across disciplines and various areas of knowledge ([Fisher and McAdams, 2015](#)).

[Rampasso et al. \(2019\)](#) carried out a survey to investigate student opinions on sustainability. The study did not specify the sustainability factors (economic, environmental, and social), and students were left to make their own judgments on whether the parameters utilised in the survey linked to social, economic, or environmental aspects of sustainability. Interestingly, [Rampasso et al. \(2019\)](#) observed that the students did not examine certain social components of sustainability, such as criteria connected to employees and local communities, in their sustainability study. [Rampasso et al. \(2019\)](#) feels this is due to how the curriculum is designed, as students do need to consider these elements when studying. However, other aspects related to social sustainability received greater attention, such as "sustainable aspects in operations networks" and "customer, development, or new products and services." In this study, environmental factors ranked third, while ethical considerations came in last.

Dagiliūtė et al. (2018) observed that social sustainability is the most essential part of sustainable education, and Rampasso et al.'s (2019) findings confirm that conclusion. However, as previously indicated, there is little evidence to support Rampasso et al.'s (2019) claim that a lack of environmental sustainability courses in universities is to blame for the lack of interest in environmental studies. Fisher and McAdams (2015), on the other hand, argue that the emphasis on environmental sustainability has distorted students' understanding of what sustainability really means, which may explain why they are unable to provide a clear definition of sustainability when asked. Fisher and McAdams (2015) also stated that what students deem essential has a direct link to the courses that they study. For example, taking a course in environmental sustainability might inspire students to interact with environmental studies more. Wilson et al. (2015) supports this suggestion because, as defined by students, sustainability was more likely to include environmental considerations.

According to Aginako and Guraya (2021), environmental sustainability has a greater impact on students because of its prominence in the curriculum. They undertook a study on Spanish universities, revealing that there was more environmental sustainability integrated into the curriculum than social and economic. Even though their major participants were electrical engineering, industrial electronic, automated engineering, and mechanical engineering, they all deemed the environment to be the most essential pillar of sustainability, followed by social and economic sustainability.

That is why engineering students' reluctance to include sustainability in their disciplines is more evident. Wilson et al. (2015) suggested that this reluctance stems from students' judgments that sustainability is unconnected to technical principles or irrelevant to their disciplines. Because engineering students have so many conflicting ideas about sustainability, it is possible that they will be reluctant to accept sustainability as an essential component of their education.

Students may regard sustainability as a noble goal, but consider it to be both ill-defined and unattainable. It was also discovered that engineering students' conceptions of sustainability are a vast and complex collection of discipline-specific definitions, with students failing to recognise the global and national implications of their disciplines (Wilson et al., 2015). This observation emphasises the importance of comprehensive sustainability education from an interdisciplinary

perspective in order to ensure engineering students are well-equipped to tackle today's real-world problems.

Fisher and McAdams (2015) discovered that students' views on sustainability were greatly influenced by the types of sustainability courses they took, not the quantity of courses they took. As a result, students exposed to natural science courses like biology, geology, and ecology may interpret "sustainable" in a broader environmental context. What Fisher and McAdams (2015) learned may be interpreted as meaning that students' perceptions of sustainability are shaped more by exposure to a particular subject or concentration in a class than by continuing exposure to sustainability-related courses. That implies that whatever students are introduced to during their studies influences what they believe about sustainability.

The Fisher and McAdams (2015) research further supports the notion of sustainability courses for certain fields throughout their degrees, and suggests that sustainability has to be treated, not just in terms of its environmental aspect, but also in terms of its social and economic development standpoint.

Wilson et al. (2015) noted mechanical engineering students who failed to consider renewable materials, extended product lifespan, environmental consequences of manufacturing processes, and end-of-life as sustainable product designs. While product design is one of the primary technical skills in mechanical engineering, and includes all of the previously mentioned aspects, students did not consider these sustainability concerns because they commonly thought of sustainable design as a separate and secondary process from the basic product design approach.

This problem was not restricted to one discipline, as Wilson et al. (2015) show that even civil engineers did not understand what sustainable design meant in their professions. In some cases, students of civil engineering recognise sustainable design only as the use of recycled materials. Electrical and electronic engineering students described sustainability in more focused, operational terms, such as longer product life, reduced energy usage, decreased use of material, minimum toxicity of materials, and improved disposal (Atlee and Kirchain, 2006). They felt the importance of reducing the need for product repair and extending

product lifespan by implementing a better design. Interestingly, however, electrical and electronic engineering students did not recognise power and renewable energy in terms of sustainability (Wilson et al., 2015; Atlee and Kirchain, 2006).

These examples demonstrate that each discipline perceives sustainability in a unique manner. Furthermore, engineering students appear more comfortable providing a technical definition that relates to sustainability rather than a broad definition. Identifying a straightforward, trustworthy, and consistent definition of sustainability that is repeated throughout an engineering programme therefore seems to be the first and most crucial step in making sustainability an accessible and realistic goal (Wilson et al., 2015; Fisher and McAdams, 2015; Björnberg et al., 2015; Zeegers and Clark, 2014).

When it comes to sustainability education in engineering, Zeegers and Clark (2014) agree with Fisher and McAdams (2015) and call for a well-rounded course design. Zeegers and Clark (2014) found that while there had been some shifts in student perception, it was unclear whether students' perspectives include all of the pillars of sustainability. Zeegers and Clark (2014) found that many students focused the social, rather than environmental, impact of the course. They argue that, in order to provide graduates with the information and skills necessary to make a major contribution to the realisation of a sustainable future, students must be given the opportunity to produce their own definitions of sustainability (Björnberg et al., 2015; Zeegers and Clark, 2014).

It is difficult to pin down when and who first used the term "sustainable engineering". The significance of the term, however, is well-defined for those who believe that engineers are involved in imagining and constructing a sustainable future (Allenby et al., 2009). Engineering for sustainable development attempted to incorporate sustainable development principles into the execution of engineering activities (Allen and Shonnard, 2011). As a result of this endeavour, a wide range of engineering disciplines and methodologies, including industrial ecology, green engineering, and earth systems engineering, were established (Bell, 2011).

Due to the challenging nature of sustainability, it is difficult to define sustainable engineering. Sustainable engineering has inherited the vagueness and ambiguity of the concept of sustainability. However, "development that meets the needs of the present without compromising the ability of future generations to

meet their own needs” is still the most commonly used definition for sustainable engineering (Brundtland et al., 1987). Sustainable engineering is defined by the UNESCO Engineering Initiative as “the process of using resources in a way that does not compromise the environment or deplete the materials for future generations” (Marjoram et al., 2010; UNESCO, 2021).

Similarly, engineering sustainability can be described as a specialised definition of sustainability. To put it another way, engineering sustainability means providing engineering services that don't harm the environment and are acceptable to the communities and people who will use them in the future (Rosen, 2012). Engineering sustainability is defined by Rosen (2008; 2009) as the provision of services for all people in a manner that is sustainable. This means that the services must be provided in ways that, both now and in the future, are sufficient to provide basic necessities, affordable, not detrimental to the environment, and acceptable to communities and people.

In order to illustrate fundamental contrasts between understandings of sustainability in engineering and sustainable development, Seager et al. (2012) introduced three main approaches to sustainability engineering: “business as usual”; “systems engineering”; and “sustainable engineering science” . As Seager et al. (2012) describe it, “business-as-usual” thinking tends to be too optimistic about the potential of technology to enhance human life. In other words, it assumes that the introduction of new skills would inevitably enhance environmental, social, and economic quality. By using a “business-as-usual” approach, it is possible to overlook environmental and social aspects of sustainability in favour of economic factors.

As a result of the “systems engineering” approach, as Seager et al. (2012) explain it, engineering systems are often optimised for conventional goals such as cost reduction or rate of return optimization, rather than a more comprehensive approach to the three main pillars of sustainability. In this approach, environmental quality and social objectives are recognised as design goals in their own right, which need a trade-off analysis with regard to one another and to cost. However, engineering optimization within ecological constraints, as well as triple-bottom-line approaches, are marginal analyses that disregard scale. Such approaches are therefore susceptible to the criticism that new technologies that produce

goods more efficiently (and thus more cheaply) will always be preferred. For example, in a "systems engineering" approach, hybrid cars appear to exemplify a technology that incorporates all triple bottom line considerations in design.

"Sustainable engineering science" represents a paradigm change in the way science handles technological and complex systems. This approach refers to scientific principles that operate at the interface between industry and nature (Clark and Dickson, 2003). Seager et al. (2012) explain that, if the typical solutions of the industrial period consider the cost per watt, the "sustainable engineering science" approach examines the whole life cycle. Consequently, all systems are examined from a larger perspective, with more potential than previous methods. Seager et al.'s (2012) main argument is that, while technological approaches to sustainability can be understood as pluralistic and evolve from one paradigm to another, "sustainable engineering science" represents a major departure from other approaches.

Few disciplines, especially the older disciplines that have dominated engineering for a long time, have tried to incorporate sustainability in their curriculum. Since the early 1990s, for example, there has been concern about electronic product-related dangers, notably the end-of-life difficulty of disposing of numerous electronics devices containing hazardous elements such as lead, cadmium, mercury, and so on. Restriction of Hazardous Substances (RoHS) and the Waste Electronic and Electrical Equipment (WEEE) directive were two measures enacted by the UN to mandate the elimination of hazardous substances from electronic products and the implementation of Extended Producer Responsibility, whereby producers of electronic goods are made to take full accountability for the entire product's life cycle. This law gives electronics manufacturers leeway to come up with creative solutions to recycling problems and pushes them to compete on the basis of product design and efficiency (Smith, 2009).

Hankammer et al. (2021) tried to test whether consumer mass customisation could help with sustainability in consumer electronics. They thought that corporations might influence consumer sustainability by giving alternatives that, in the end, have a reduced environmental effect by simply being upfront about product sustainability facts. They conducted four studies and discovered that offering extensive product information might aid in sustainability. Hankammer

[et al. \(2021\)](#) show that the company and product designer were solely responsible for specifying sustainable items while enabling the consumer to choose what worked best for them, enhancing customer happiness.

[Braun \(2011\)](#) recommends incorporating sustainability into degree programmes and particular courses with discipline-specific designations. Braun's effort to incorporate sustainability in an integrated circuit course included learning outcomes heavily influenced by design and efficiency, such as modelling electronic devices and explaining their characteristics, use of semiconductors, and learning about circuit models and diode behaviours ([Braun, 2010; 2011](#)). Based on the assessment results, students were able to enhance their sustainability analysis skills ([Braun, 2011](#)).

According to [Braun \(2010\)](#) and [Azapagic et al. \(2005\)](#), specialised courses, in-depth case studies, hands-on projects, and curricular integration are the best approaches to teaching students about sustainability. However, they claim that there are few resources available to integrate sustainability as part of specialised training for instructors. Exposing students to several definitions of sustainability might help alleviate some of the reluctance students may experience when asked to integrate broad sustainability concepts into their discipline-specific lessons. Similarly, students may tackle technological challenges by combining technical communication, critical thinking, sustainability analysis, and systems thinking ([Braun, 2011](#)).

However, there is little room for implementing sustainability education in the engineering curriculum. Because traditional engineering culture holds the core belief that engineering skills such as mathematics, statics, dynamics, and material science, should constitute the primary curriculum, students struggle to connect with sustainability projects in their degrees. Students seem to consider sustainability to be general knowledge, rather than discipline-specific knowledge relevant to their specific projects ([Olsen et al., 2013](#)).

The profession of software engineering is important to long-term sustainability because software systems affect so many parts of our lives. However, as [Becker et al. \(2015\)](#) mentioned, in software practice, the emphasis is almost always on the immediate implications and practical advantages of software products and platforms. Long-term thinking in software design has several advantages.

Software drives automation and dematerialization in virtually every area. Our resource and information access are increasingly influenced by software design decisions rather than deliberate choices made by people. Thus, designing software systems carries societal obligations that go well beyond those stated in current codes of ethics for computer professionals (Becker et al., 2015).

Despite recent improvements in design for software maintainability, as well as considerations that extend beyond the immediate technical and/or marketing characteristics of the system, a shared knowledge of how to integrate sustainability into software design is lacking in higher education (Becker et al., 2015). Consequently, significant advances in the fields of software maintenance, programme comprehension, reverse engineering, re-engineering, mining software repositories, software migration, and software process improvement were made throughout the decades as the software design community evolved (Becker et al., 2015). The analysis that was gained from these studies will guide the continuous improvement of software engineering practices and enhance the quality of developing software systems.

Both software products and software engineering processes can be developed in the direction of sustainability by making ICT goods and services more sustainable over their entire life cycle, primarily by reducing the energy and material flows they require and creating, enabling, and encouraging sustainable patterns of production and consumption (Raturi et al., 2014). Requirement engineering is in a privileged position to promote sustainability thinking early in the software development life cycle. However, from a software requirements standpoint, sustainability is seldom discussed in software engineering (Naumann et al., 2015; Hilty and Aebischer, 2015). Raturi et al. (2014) introduced the concept of a “non-functional requirement” to highlight sustainability’s role in software development. Sustainable development may be aided by software engineering, which can ensure that technologies built and used today won’t hinder the capacity of future generations to do the same (Raturi et al., 2014; Naumann et al., 2015).

Non-functional requirements have been defined in various ways depending on context. Raturi et al. (2014), for example, developed a framework for non-functional requirements that can be used to help with sustainable development in software engineering discipline. This framework highlights four main aspects in software

sustainability: social; economic; environmental; and technological. [Lago et al. \(2015\)](#) propose a model to simplify the process of understanding the framework.

[Venters et al. \(2018\)](#) further emphasise the need for a framework, particularly given varying opinions on what “sustainable” means among software engineers ([Venters et al., 2018](#); [Naumann et al., 2015](#); [Hilty and Aebischer, 2015](#); [Durdik et al., 2012](#); [Penzenstadler and Fleischmann, 2011](#)). The capacity for a software system to persist through time has been the primary emphasis of formal definitions of software sustainability ([Penzenstadler, 2013](#)). The literature defines this capacity as a “first-class,” “non-functional,” or “software quality” criterion ([Penzenstadler et al., 2014](#)). [Venters et al. \(2018\)](#) describe software sustainability as “a measure of a system’s extensibility, interoperability, maintainability, portability, re-usability, scalability, and usability.” Although increased technical understanding increases the likelihood of success in terms of technical sustainability, maintaining software sustainability over the long term remains an especially difficult issue due to interdependencies between social and financial sustainability within the organisation that created the software. [Durdik et al. \(2012\)](#) point out that “in many software development projects, sustainability is treated as an afterthought, as developers are driven by time-to-market pressure and are often not educated to apply sustainability-improving techniques.”

2.3 Threshold Concept Theory

Meyer and Land developed the [Threshold Concept Theory \(TCT\)](#) in 2003, stating that every discipline includes troublesome concepts that transform the learner when they are grasped. This change will affect the learner’s thinking about (perception of) the concept. A threshold concept is differentiated from a ‘key’ or ‘core’ concept in that it is more than a building block towards discipline-specific knowledge ([Harlow et al., 2011](#)). TCT have been connected to ontological shifts ([Meyer et al., 2010](#)), identity alterations, and subjectivity transformations that occur as a result of a learner’s previous conceptual framework being reconfigured. These transformations are critical to understanding what it means to be an artist, economist, or engineer ([Harlow et al., 2012](#)). Unfortunately, it is threshold concepts that students often struggle with and where they frequently get “stuck” ([Davies, 2006](#); [Harlow et al., 2011](#); [Meyer and Land, 2003](#); [2005](#)). Initially, five qualities were suggested to aid in the identification of threshold concepts

in any discipline. These characteristics are further described and explained in Section 2.3.1.

Encountering the unknown has always hindered humanity's development, but every now and then, when the human race pushes ahead to cross a barrier, they advance (Meyer et al., 2010). The belief that the planet was flat led people to picture themselves falling over the edge of the earth, for example, stopping them from venturing and discover new landmasses. Once they crossed this threshold and went out to discover unknown oceans, however, everything changed. This serves as a reminder that, in order to advance, one must conquer the fear of what lies beyond, of the unfamiliar, the unknown, and of danger. 'Real learning' necessitates that we go into the unknown (Meyer et al., 2010). Another good example of crossing a threshold mentioned by Scott and Harlow (2012) is learning to ride a bike.

Unlike breathing, seeing, and eating, riding a bicycle is not instinctual. Individuals must acquire the ability to ride a bicycle. To assist with this, a child's parents might first equip the bike with side wheels, allowing the youngster to overcome his or her fear of falling. The threshold is the first step in overcoming fear. After some time and observation of his/her peers, the child may begin riding the bike with one spare wheel to practise maintaining balance, and eventually, with practice, the child will be riding the bike without recalling the procedure. Each step of learning to ride a bike represents a threshold because it affects the child in some way. The critical thing to understand here is that this is an irreversible process of learning.¹ Once someone has learned to ride a bike, they will usually not be able to unlearn it. As a result, the expression 'as easy as riding a bike' was coined. Meyer and Land (2003, p. 1) illustrated their theory with the following example of 'heat transfer' as a threshold concept in the discipline of cookery:

Imagine that you have just poured two identical hot cups of tea (i.e. they are the same temperature) and you have milk to add... You add the milk to the first cup immediately, wait a few minutes and then add an equal quantity of milk to the second cup. At this point which cup will be cooler, and why? (The answer is the second cup, because in the initial stages of cooling it is hotter than the first cup

¹Scott and Harlow (2012) tested this by asking someone to ride a bike after a decade of not riding it, they were able to remember it in less than 10 seconds

with the milk in it and it therefore loses more heat because of the steeper temperature gradient.)

Meyer and Land (2003) noted that, in every field, certain ideas are crucial to that field's knowledge. Meyer and Land (2003) utilised a metaphor to illustrate how this process works, describing learning a threshold concept as stepping through a gateway. The learner must be at a stage of limited comprehension while entering the portal to pick up the threshold concept about his or her discipline. Think of the threshold concept as a gateway to a new mental realm. Through this portal, you may gain access to a line of thought about a topic that was previously unavailable to you, expanding your horizons and enriching your understanding of the world (Davies and Mangan, 2005; Meyer and Land, 2003).

TCT is primarily utilised in higher education to assist students and instructors to enhance the quality of the learning process. If instructors' main objective is to foster students' comprehension of the topic, it is critical to begin somewhere and make sense of important and challenging ideas (Cousin, 2006). TCT emphasises the importance of disciplinary core concepts that benefit not only students but also instructors. As a result, it has the capacity to change, not just the ontological, but also the conceptual (Cousin, 2006; Meyer et al., 2010). Typical examples include the philosophical concept of 'personhood'; the physical concept of 'gravity'; the electrical engineering concept of 'reactive power'; the mathematical concept of 'limit'; and the environmental science concept of 'uncertainty' (Meyer et al., 2010). As such, there are several perspectives through which TCT may be analysed. A divide exists between the views of students and teachers on this issue. However, researchers should know where to search for threshold concepts in the curriculum if they research TCT characteristics and employ a threshold concept framework.

2.3.1 Threshold Concept Characteristics

Meyer and Land (2003) stated clearly that threshold concepts are distinct from fundamental ideas in any field. Core concepts are those that enable an individual to progress in understanding, whilst threshold concepts are those concepts that enable progression and/or alter the individual's view of the discipline. In light of this, the authors identified five distinct features of TCT, each of which is

discussed below. One critical point from their explanation of the traits, however, is that not every threshold concept will show all five of these characteristics.

Transformative

Humans are generally adaptive and constantly changing their perspective on the world; humans become what they frequently do, as their identities and personalities are influenced by frequent behaviour and experience. To recognise threshold concepts, one must undergo a transformation ontologically and conceptually. Students' new knowledge will be incorporated into their biography, transforming who they were and how they previously saw the world ([Barrett et al., 2017](#); [Cousin, 2006](#); [Sandri, 2013](#)).

The transformational nature of TCT has been highlighted many times and is the only one of the five fundamental qualities that is considered essential. Apart from experiencing a shift in their knowledge of a discipline as a result of grasping a threshold concept, an individual may also feel a transformation in their own identity as a result of the changed viewpoint. Additional transformations may occur in an individual's activities or behaviour if such transformations are directly related to their actions. [Meyer and Land \(2003\)](#) provide an excellent example of students from sports and science developing confidence in water sports. This newly-gained confidence altered students' perceptions of aquatic instruction and encouraged them to increase their participation in outdoor activities. The transformative quality of TCT is important since it has the potential to alter, not just the individuals, but also the community ([Barradell, 2013](#); [Cousin, 2006](#)).

Irreversible

Having learned a threshold idea, it is extremely challenging to unlearn it. This is what is meant by the irreversible quality. Thus, once a person has achieved a new, altered perspective, it is difficult for them to return to their old way of thinking. Once the learner has been transformed, it is most unlikely that he/she will forget the knowledge. Especially if the information is internalised and becomes part of one's body of experience, shedding it can be a daunting task ([Cousin,](#)

2006; Meyer and Land, 2003; Sandri, 2013). Meyer and Land (2003) implied that the majority of threshold concepts would exhibit this characteristic.

Integrative

Another characteristic of TCT that was addressed by Meyer and Land (2003) was its integrative nature, but this trait may not be universal for all threshold concepts. This characteristic denotes how a person learns to perceive and make connections between the many ideas and concepts in a subject as they begin to comprehend that subject. Threshold concepts can renew/change the relatedness of other subjects; in other words, they are capable of permitting the learner to associate topics which were previously hidden from view (Barrett et al., 2017; Cousin, 2006; Meyer and Land, 2003). Threshold concepts have the ability not only to transform understanding of a particular subject, but also to integrate, bringing to light previously hidden connections between other subjects (Sandri, 2013). Meyer and Land (2003) noted that only so much integration is feasible, and therefore links between concepts within a field may not be able to be established.

Bounded

Meyer and Land (2003) described threshold concepts as often (but not necessarily always) bounded. As the name implies, the boundedness of a threshold concept refers to its ability to aid in the definition of boundaries that exist across different disciplines. To put it another way, although one discipline's epistemological and ontological views may make a threshold concept relevant, another discipline's beliefs may make that threshold concept inapplicable within their domain. The notion of opportunity cost in economics was used as an illustration. Opportunity cost is not as intuitive for those who have not studied economics. Threshold concepts can be a form of disciplinary possession, and as such, their presentation in a curriculum may tend to foster solid understanding (Cousin, 2006; Meyer et al., 2010).

Troublesome

It is hard to understand and grasp threshold concepts as they are transformative and irreversible, therefore making them troublesome for learners to engage from the first encounter (Barrett et al., 2017; Cousin, 2006; Davies, 2006; Meyer and Land, 2003; Sandri, 2013; Scott and Harlow, 2012). There are a few reasons as to why these concepts are troublesome; they may, for example, include counter-intuitive, alien, incoherent, ritual, etc. knowledge. (Davies, 2006; Davies and Mangan, 2005; Meyer and Land, 2003). Troublesomeness is one of the most important characteristics of TCT because of the importance placed on “troublesome knowledge” by Meyer and Land.

Meyer and Land (2003) made it very apparent that their concept of a troublesome characteristic was based on Perkins’ (1999) description of four distinct types of troublesome knowledge. The first of four types of troublesome knowledge is inert knowledge, which is acquired but not actively used by a person (Perkins, 1999). Meyer and Land (2003) explored how some threshold concepts may become inactive knowledge if they are difficult to link to other ideas within a field or to the actual world. The second type of troublesome knowledge is ritual knowledge, which refers to knowledge that is utilised ritualistically and has little significance (i.e. using memorised formulae ritualistically and failing to articulate how and why the ritual works). The third type of troublesome information is conceptually difficult knowledge. If students are prone to misunderstanding an idea, or find it odd or complicated, this indicates that the idea is conceptually challenging. Although conceptually difficult information exists in many fields, it is most often found in mathematics and the sciences (Perkins, 1999). Perkins (1999) recognised that more categories may exist; his final listed category, however, was alien knowledge. This is information that comes from a viewpoint other than the student’s. It is critical to emphasise that every piece of information has the capacity to exist in many troublesome forms. Each of these manifestations exemplifies a manner in which a threshold concept may be inconvenient for a student.

In addition to Perkins’ four types of troublesome knowledge, Meyer and Land discussed two further categories: tacit knowledge; and troublesome language. Tacit knowledge refers to implicit information in any field that practitioners may not express directly. Troublesome terminology refers to the jargon that is used

within each field and may be difficult for students to comprehend at first. This difficulty may be exacerbated further when discipline-specific instructors try to communicate complicated ideas using new language that students have yet to comprehend.

Understanding TCT could help in the tertiary learning and teaching process (Harlow et al., 2011; Meyer and Land, 2003; Meyer et al., 2010; Peter et al., 2014). Nevertheless, mastering a threshold concept is a transition from known reality to the unknown (Harlow et al., 2011; Meyer et al., 2010; Scott and Harlow, 2012). This transition has been compared with a gateway or portal in which learners will go through states of mimicry (liminality space) in order to fully grasp the subject.

2.3.2 State of Liminality

TCT was characterised as a portal through which students must pass in order to properly comprehend a subject (Cousin, 2006; Davies, 2006; Meyer and Land, 2003). Meyer et al. (2010) suggested that learning involves the occupation of a liminal space during the process of mastery of threshold concept. Cousin (2006) linked this stage to adolescence - neither adults nor children. Moving through this portal is popularly described as the "light bulb" or "Aha" moment, in which students' understanding of a topic is initially not fully developed but, once the concept has been fully absorbed, students will have a moment of realisation of fully grasping the knowledge (Harlow et al., 2012; Scott and Harlow, 2012).

Grasping knowledge with the aid of TCT is conceivable; yet, the change that learners must go through in order to completely internalise an idea is transformative, permanent, and, most all, troublesome. Kabo and Baillie (2009) proposed the liminal spectrum, which ranges from pre-liminal to post-liminal states. Each learner's journey through the liminal spectrum is unique, based on their backgrounds and comprehension of the concept being introduced to them (Cousin, 2006; Davies, 2006; Meyer and Land, 2003). As a result, learners will navigate the liminal space in a different way. Some will go through it easily, while others will take more time and effort to get through it (Harlow et al., 2011).

The liminal state metaphor might be compared to a dark tunnel, through which the learner will be transformed, with irreversible implications, only if the learner goes through the troublesome process. As a result, the liminal tunnel, rather

Figure 2.3

An original visual representation of the 'liminal tunnel' adapted from work by [Rattray \(2016\)](#) and [Kabo and Baillie \(2009\)](#)

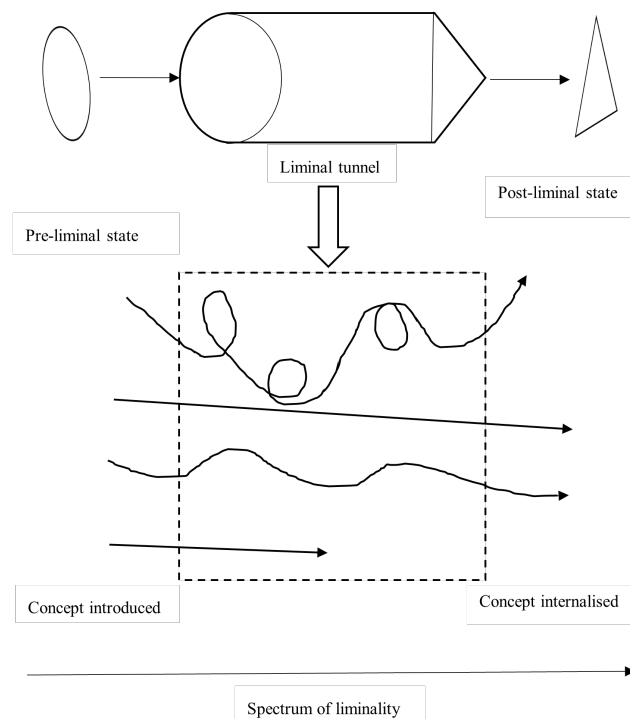


Figure note: The learner's journey has been beautifully illustrated here; some will cross with ease, some will struggle, and some will never leave liminal space. The transformation where the learner paradigm is shifted has been illustrated from pre-liminal space to post-liminal space.

than liminal space, provides a useful metaphor because it encompasses both conceptual and ontological transitions ([Cousin, 2006](#)). Figure 2.3 was inspired by [Kabo and Baillie's \(2009\)](#) and [Rattray's \(2016\)](#) interpretations of the liminal state; I integrated both of their concepts to create what I believe is the best analogy for the liminal tunnel and liminal space together. The learner will enter the tunnel, also known as liminal space, from the pre-liminal condition and will emerge transformed. The reason I revised [Rattray's \(2016\)](#) liminal tunnel is that we can clearly see the shift that the learner has gone through in Figure 2.3. As a result, this transition is irreversible and troublesome. Using the triangle to represent the post-liminal stage illustrates that the learner is more focused compared to the pre-liminal phase.

2.3.3 Threshold Concepts in Sustainability

The idea of sustainability has gained widespread acceptance and has been put into practice ever since the United Nations first introduced it to the world (UNESCO, 1987). Sustainability is a common organising principle in many organisations, including the World Bank, local health clinics, and even prestigious publications. Equally groundbreaking is the unusual agreement reached by governments and non-governmental organisations (NGOs) on a list of 17 global Sustainable Development Goals (SDGs), which set forth specific goals for resolving a variety of social and environmental issues, from overfishing to poverty (Loringa, 2020). Researchers have spent a lot of time examining the paradigmatic nature of sustainability and how sustainability education can contribute to a corresponding shift in our ethical and epistemological frameworks. These researchers work in fields like environmental and sustainability education, education for sustainable development, and transformative learning (Sterling, 2011; Barrett et al., 2017; Burns, 2018; Sandri, 2013; Loringa, 2020).

However, the concept of sustainability has also frequently come under fire for being ambiguous and uncertain. Despite setting the tone for the last three decades, the UNESCO (1987) report has led to many sustainability initiatives that have been criticised for failing to bring about paradigmatic change. In particular, some initiatives have been accused of not sufficiently incorporating ecological concerns or shifting the focus of development from unrestricted economic growth to growth in human well-being and justice (Loringa, 2020). For a long time, sustainability has been panned; Solow (1991) captured this critical attitude when he called it “ambiguous,” and “vague.”

In this context, threshold concepts could be used to bring about a meaning and develop a common understanding for sustainability education. Successfully navigating students through the transitional zone between established practices and emerging ideas requires more than just repeating threshold concepts (Burns, 2018). In this section, I will share the literature I have discovered that explores the relationship between threshold concepts and sustainability. While I may not necessarily endorse all the viewpoints expressed, the various perspectives can facilitate connections and enhance our comprehension of the intricate nature of sustainability.

Magnier (2015) has acknowledged that sustainability is a threshold concept. Sustainability was described by Magnier (2015) as a foreign concept that most students find difficult to grasp. Since Solow (1991) also compared sustainability to being ambiguous, as was already mentioned in the preceding paragraphs, Magnier (2015) is not alone in thinking that sustainability is vague and unclear. According to Magnier (2015), environmentalists and economists must overcome their reluctance to examine environmental-economic interactions using a method that combines constructive results with normative standards; they must also overcome their fears of acknowledging the value of economy to society. Prioritizing sustainability in terms of the environment or the economy inherently is neither bad nor good because of the ambiguity of the term. Magnier's (2015) research therefore exhorts universities to personalise sustainability for each student.

Barrett et al. (2017) also argue that sustainability is a threshold concept, but with the key distinction of introducing non-human, natural, and spiritual connection with humans in a context in which not everyone could easily connect with nature and see it as a living being. Aside from non-human and natural power, Barrett et al. also heavily emphasise emotions. Barrett et al. (2017) hold a position that is supportive of constructivism, and argue that it is challenging for students to relate to sustainability because of students' different world-views, the fact that knowledge is relational, and the fact that there are various ways to approach sustainability. Barrett et al.'s work emphasises systems and system thinking, which suggests that the relationship between nature and humanity is a system. It shouldn't come as a surprise that the growing emphasis on multiple forms of knowledge in sustainability science and practice has turned into a troublesome concept (Barrett et al., 2017; Loringa, 2020). Some have claimed that traditional and local knowledge poses a threat to efficient management. Others, on the other hand, have developed complex justifications for omitting or undermining the legitimacy of local knowledge and stewardship (Loringa, 2020).

According to Roberts (2011), "education for sustainability" encompasses, but is not limited to, imagining a better future, critical thinking, partnership, system thinking, and improved decision-making. Roberts compared the traits of each of these elements to those of threshold concepts and concluded that sustainability includes both transformative and problematic elements. In-depth research on the liminality spectrum was also carried out by Kabo and Baillie (2009), who

discovered that social aspects of sustainability are a threshold concept in engineering education.

The skills most frequently mentioned for sustainability are systems thinking and holistic thinking. [Phelan et al. \(2015\)](#) discussed the need for graduate students to exhibit a cogent and sophisticated understanding of various environmental and sustainability approaches in society using systems thinking in a report by the Australian government. [Phelan et al. \(2015\)](#) emphasises the significance of students demonstrating a solid understanding of both theory and practice in their field of study related to sustainability. Although useful, these skills were primarily geared toward environmental education, and up until this point, all publications had only mentioned systemic thinking as a subset of other qualities.

By contrast, [Sandri \(2013\)](#) thought that the only key ideas in engineering education for sustainability were systems theory and systems thinking. To practice sustainability, according to [Sandri \(2013\)](#), it is essential to comprehend systematic approaches. The use of various policies that encourage [Sandri \(2013\)](#) to view sustainability as a system is required of learners as they apply sophisticated solutions to problems encountered around the world. Once systems thinking transforms learners, they are unable to revert to their previous behaviour. According to [Meyer and Land \(2005\)](#), dealing with threshold concepts entails helping students internalise them while also altering their conceptual frameworks and meaning. According to [Meadows et al. \(2002\)](#), systems thinking enables us to identify opportunities and problems to solve their root causes.

Understanding complexity, or practising systems thinking, requires eschewing mechanical reasoning in favour of a focus on the numerous interactions among a system's various components ([Meadows et al., 2002](#)). Understanding complexity involves changing one's conceptual perspective from seeing things as the summative results of a causal chain to seeing them as the result of interactions and feedback among various drivers and constraints that work together to produce emergent results. The sustainability paradigm fundamentally rejects the notion of panaceas ([Loringa, 2020](#)), largely as a consequence of recognising complexity. The messy nature of the sustainability issues we face is highlighted by complexity ([Meadows et al., 2002](#); [Sandri, 2013](#); [Loringa, 2020](#)); additionally, one-size-fits-all solutions are ineffective and likely to have unintended consequences due to the specific characteristics of local contexts ([Lozano, 2008](#);

[Loringa, 2020](#)). Complexity also forces students to find solutions based on societal change, rather than focusing only on technological solutions, and thus makes clear that one-size-fits-all solutions are inappropriate ([Loringa, 2020](#)).

The realisation that sustainability in nature is a scale-dependent phenomenon is also a threshold concept because complexity has made adaptation a key component of sustainability ([Loringa, 2020](#)). Engineers have a chance to counter the constantly shifting natural system if they accept the constant change and become accustomed to adapting designs and solutions. However, this means that universities' strategies must be altered. In order to achieve a long-lasting solution to engineering problems, it is necessary that the adaptations be created within a step-by-step plan which will, in time, strengthen resilience of the overall system. However, recognizing the value of collaborative institutions, which can be strong and successful locally, presents a challenge because it goes against the fundamental tenet of neoliberal state-based natural resource management, that resources must be contained by markets and policies ([Loringa, 2020](#)).

2.4 Key Competencies in Sustainability

The term “competencies” refers to a set of multiplexes of knowledge, abilities, and attitudes that can ensure success in tackling real-world problems, challenges, and opportunities associated to sustainability. (Wiek et al., 2011; de Haan, 2006; 2010). These skills are versatile enough to meet any problem that may arise in relation to sustainability (für Gesundheitsforschung und Bildung, 2021; Sidiropoulos, 2014; Hauenstein, 1998). As Wiek et al. (2011) point out, there has been a tremendous emphasis on sustainability competencies over the previous decade; nevertheless, while the number of competencies is potentially inexhaustible, “laundry lists” without transparent selection criteria dominate the discourse. As a result, this section will concentrate on the most well-known frameworks that serve as the cornerstone for sustainability capabilities.

For sustainability education, making an empirical argument for the needed competences is an essential step. That is why this study seeks to use TCT to add to the needed empirical evidence. The systematic literature review on critical competences by Wiek et al. (2011) shows a lack of empirical evidence, depth, and rigour. Furthermore, there is no evidence that graduates are prepared to deal with sustainability issues. According to Wiek et al. (2011), the literature does not adequately operationalise important competencies through the design of specific learning objectives and evaluation procedures. As a result, the literature does not completely handle all crucial components, particularly the methodological aspects of core talents needed in sustainability.

As we progress from this overview to the substance of key sustainability competencies, it is necessary to describe the sustainability theory that was used to identify and define essential skills. Some more comprehensive perspectives include, for example, systems thinking ability, anticipatory ability, Gestaltungskompetenz, or Heads, Hand, and Heart. However, these competencies cannot substitute for the unique sustainability perspective that must be used when establishing and developing sustainability courses (Wiek et al., 2011).

Is it necessary for each student to gain all competencies? As with any other field, a balance between specialisation and generalisation is prudent. Given their limited time and capacity, it appears plausible that students would develop in-depth

competence in one or two of the critical abilities while maintaining a solid foundation in the others. Sufficient rigour also relies on the academic programme's level. Students pursuing undergraduate, masters, or doctorate degrees must adhere to distinct standards. However, consolidating these standards across multiple universities, programmes, and communities will take time, which is critical for establishing the sustainability field in the academic environment and beyond. According to [Clark and Dickson \(2003\)](#), the field of sustainability is in a state of flux because it is still in its infancy. It is a creative space where old and new ideas and techniques can be tested and polished. It is a collaborative effort. The fact that the sector is problem-driven means that sustainability will continue to be a dynamic process. As the field and the problems grow, so will our knowledge of the types of skills that will be necessary.

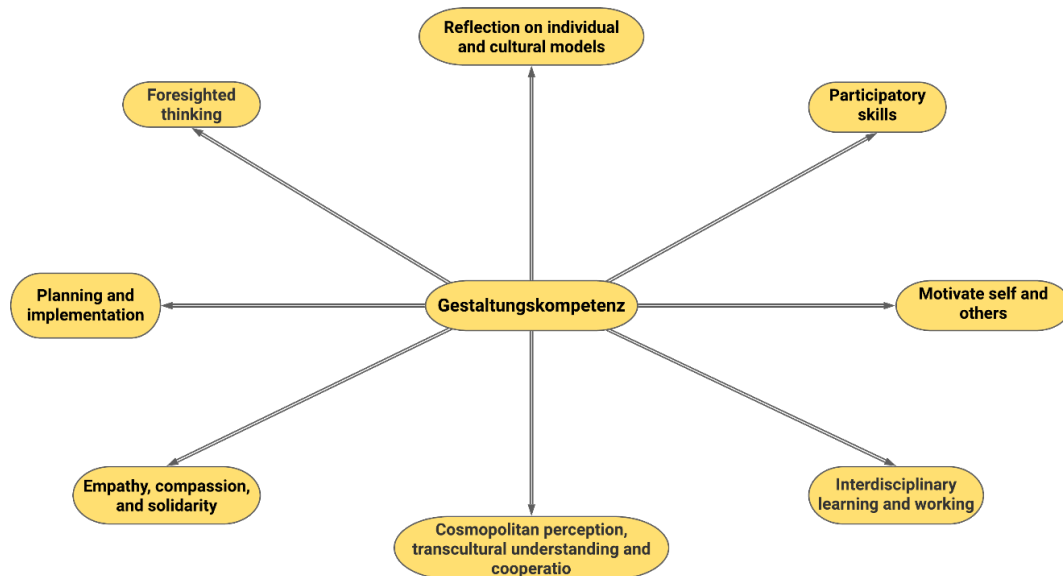
2.4.1 Gestaltungskompetenz

Gestaltungskompetenz (Figure 2.4) is a concept developed by the German BLK '21' programme which prompted the introduction of education for sustainable development in 1999. Gestaltungskompetenz can be translated as "shaping competencies" and "the distinct ability to act and solve problems". The end goal of this program was that students who possess Gestaltungskompetenz could assist in modifying and shaping the future in terms of environmental, social, and economic sustainability. That made Gestaltungskompetenz more than a concept; it captures possessing the necessary skills and competencies to make the right decision towards sustainable development ([de Haan, 2006; 2010](#)).

Gestaltungskompetenz is competencies-oriented, and the main difference between syllabus- and competence-oriented education is the focus on input vs output. Syllabus-oriented education prioritises input: it asks what subject should be taught. However, competencies-oriented education focuses on output, and it seeks ability, competencies and problem-solving skills that students should have. The main advantage of competencies-oriented education is that student

Figure 2.4

Summary of key concepts in *Gestaltungskompetenz* adapted from [Driza and Antonini \(2013\)](#)



learning is not bounded by the classroom wall. What makes *Gestaltungskompetenz* essential is its direct relationship with systems thinking and holistic thinking. Furthermore, it supports the constructivism paradigm. Combining systems thinking, holistic thinking, and *Gestaltungskompetenz* with Threshold Concept Theory could help sustainability curriculum developers to move each discipline of engineering under the umbrella of sustainability, while ensuring that the course and students are not alienated ([de Haan, 2006](#); [Driza and Antonini, 2013](#); [Wals and Blewitt, 2010](#)).

Systems thinking and *Gestaltungskompetenz* are inextricably linked, as demonstrated by the essential competencies listed in [Table 2.2](#). Foresight thinking is a type of systems thinking in and of itself. Another relationship that has been overlooked is the one between situated learning and *Gestaltungskompetenz*.

Table 2.2

Gestaltungskompetenz in sustainability, adapted from de Haan (2006); Driza and Antonini (2013); für Gesundheitsforschung und Bildung (2021) - short summary of a few important competencies in Gestaltungskompetenz

Competence	Short summary
Foresighted thinking	Deal with uncertainty Being able to think beyond the present The future is open and can be shaped Present action's effect on future Identify potential hazards and mitigate them for the future Ingenuity, creativity, and imagination is a must for this competence
Interdisciplinary work	Collaboration of different scientific fields and cultural traditions Knowing how to identify and understand system relations Knowing how to deal appropriately with complexity
Interdisciplinary learning	Multi-discipline problem-solving skill Cooperation of different fields on a problem using similar methods Specific complex problem that requires drawing on a range of fields to be solved
Transcultural understanding	Ability to identify phenomena in the context of global relations Widen the perception, look for the global view Ascend from local and national perspective to worldwide to solve complex global social problems Desire to learn from other people
Participatory skills	Students' interest in shaping a sustainable world Active decision-making and eagerness to emphasise life
Planning and implementation	Knowing relationships between knowledge, attitudes, intentions and human actions Ability to assess the resources needed for action with sustainability in mind. Differentiate desire and doing from thinking Learning to consider the rapid changeability and temporary nature of knowledge
Empathy, compassion and solidarity	Balance between poor and rich International solidarity Justice for all
Self-motivation and motivating others	Willingness to change and motivate others to change towards a sustainable future Reflect on individual culture and beliefs
Reflection on individual and cultural models	Critically analyses societal models of self and other cultures Identifying and critically examining self-interests and desires

2.4.2 Heads, Hands, and Heart

The concept of head, hands, and heart identifies a collection of learning objectives aligned with cognitive (head), psychomotor (hands), and emotional (heart) domains of learning that promote participants' own experiences in sustainability education. This concept was used by [Sipos et al. \(2008\)](#) to create a clear framework for bringing a range of competencies together. Bloom's Taxonomy ([Bloom, 1956](#)) was essential in establishing the groundwork for this approach.

The primary assumption in this framework is that students' locations of study, employment, and leisure serve as the focal point for their experiences, which help them learn how the world works and how they fit into it ([Sipos et al., 2008](#)). When the setting for sustainability education involves both the local environment of the students and the institution of higher education, conflicts of interest are certain to emerge. As a result, sustainability education must take place in both academic and community settings. Additionally, the institution and community must identify or develop essential common ground in order to reduce conflicting interests ([Gruenewald, 2016](#)).

The relationship between sustainability and education was established in [2.2.1](#). Sustainability education must be prepared to deconstruct and rebuild all facets of teaching and learning. According to [Birch \(1988\)](#), higher education in western cultures disproportionately divides knowledge into disciplines and often results in conflict between people, ideologies, and nations, thus promoting the conquest of nature and the industrialisation of the planet. Rationalism holds that knowledge is gained by relying on evidence-based, rigorous, and scientific research. This approach promotes objectivity, certainty, universality, and predictability ([Phelan, 2004](#)). The emphasis on humanist values, such as intuition, common sense, creativity, ethics, memory, and spirituality, can diminish the significance of logical thinking and lead to irrational thinking ([London, 2001](#)). Immense fatigue has developed over curricula that are insulated from the human experience and devoid of narrative, connection, and purpose ([Sipos et al., 2008](#)).

University programmes and courses that target head, hands, and heart learning objectives enable participants to have a more personal experience, resulting in significant improvements in students' knowledge, abilities, and attitudes about the three primary pillars of sustainability ([Sipos et al., 2008](#)). It provides a

straightforward technique for integrating learning processes embedded in participants' heads (cognitive domain: sustainability understanding), hands (psychomotor domain: implementation of theoretical learning through practical skill development), and hearts (affective domain: enablement of values and attitudes).

This integration is supposed to have an effect on what [Hauenstein \(1998\)](#) refers to as the behavioural domain, the ultimate goal of transformational learning. Additionally, this combination may shed light on whether sustainability has been "learned," is believed, and/or is implemented in the lives of participants, i.e., whether and how transformation occurs ([Sipos et al., 2008](#)). Action learning, community service learning, critical emancipatory pedagogy, environmental education, participatory action research, eco-justice and community pedagogy, problem-based learning, and traditional ecological knowledge are all considered crucial competencies in sustainability education.

2.4.3 Values, Knowing, Skills, and Understanding

[Sterling and Thomas \(2006\)](#) point out that biosphere systems are vital to human survival. According to the previously mentioned sustainability model, it is possible for natural systems to continue to support other systems, such as social and economic (the three pillars of sustainability), for the foreseeable future by avoiding improper development. When all basic requirements are addressed, the sustainability model encourages people to live in harmony.

The inclusion of sustainability's wide and ambiguous terminology in a university's curriculum and teaching methodology raises serious concerns. Education for sustainability, as proposed by [Sterling and Thomas \(2006\)](#), should not be merely a list of principles that may be added to an existing curriculum, but rather a significant reorientation of educational goals and methods, whose main emphasis would be ethical participation, critical thinking, and a holistic approach. [Tilbury \(2004, p. 101\)](#) describes the need for critical thinking and a holistic approach as follows:

The terms 'critical reflection', 'values clarification' and 'participative action' have become core components for Environmental Education for Sustainability These approaches provide opportunities for students: to engage in critically reflecting upon the basis of their socio-cultural values and assumptions; to identify how they are conditioned and confined by the socio-cultural structures they are operating in and, more significantly, to build their capacity as agents of change.

Rather than being a collection of "facts and figures", sustainability education should be presented in a way that encourages students to retain their knowledge long after they have completed their study. Sustainability issues are of the utmost importance. There is no simple solution for these issues, which are dynamic and ever-changing. Students and academics alike must undergo reform and change. Everyone should practise critical thinking and take a holistic approach to resolving the real-world problems we are/will be facing ([Sterling and Thomas, 2006](#)).

As mentioned at the beginning of this section, there has been a strong emphasis on sustainability competencies over the years; however, while the list of competencies is seemingly endless, [Wiek et al. \(2011\)](#) point out that the discourse is dominated by 'laundry lists' without transparent selection criteria. [Sterling and Thomas \(2006\)](#) have established a peer-reviewed competency list that evaluates and creates a relevant list of competencies that might be utilised in higher education to promote sustainability. Their work was reviewed by [Wiek et al. \(2011\)](#), and the subsection was renamed "Values, Knowledge, Skills, and Understanding" after Wiek et al.'s work. It is worth noting that this subsection will summarise the work of [Sterling and Thomas \(2006\)](#). As will be described later in [Wiek et al.'s \(2011\)](#) model of sustainability competencies, one of the primary competencies on which [Sterling and Thomas \(2006\)](#) relies is systems thinking.

[Sterling \(1996\)](#), as well as [Sterling and Thomas \(2006\)](#), provide a list of characteristics of education for sustainability as presented in Table 2.3. Since the shift to a more sustainable society affects not only students, but also senior management, professors, and support staff, [Sterling and Thomas \(2006\)](#) argue that universities face a substantial educational challenge, which they link to the "value" aspect in teaching sustainability. To put it another way, [Sterling and Thomas \(2006\)](#) make a distinction between "designed learning" and "attendant learning"

amongst the larger higher education institutes. Sustainability education's value will be decreased if the entire community isn't involved in sustainable solutions. A strong sustainability model, they argue, will lead to a "transformation" when social and pedagogical trends are completely integrated to promote educational sustainability.

Table 2.3

A summary of the important elements of education for sustainability adopted from [Sterling and Thomas \(2006\)](#)

Characteristics	Explanation
Contextual	Local economic, social and ecological environments and communities are applied first before moving on to national and worldwide contexts
Innovative and constructive	Incorporating ideas from a variety of fields and presenting strategies for a more harmonious future
Focused and inclusive	Human ecology and social development, together with equality and the future, are at the heart of a holistic approach that impacts all other aspects of society
Holistic and human in scale	It is essential that all aspects of education (e.g., curriculum and pedagogy, structures, organisation, and ethos) be regarded as a whole and are both learner-centred and socially oriented
Integrative	A focus on interdisciplinary and cross-transdisciplinary research to acknowledge the reality that no topics, causes, or problems exist in a vacuum
Process-orientated and empowering	Rather than being product-driven, the focus is on active learning rather than passive instruction, with a strong emphasis on critical thinking
Critical	With an eye toward the future, education should be a process of critical reflection on current theories
Balancing	Seeks balance between conflicting concerns (such as environmental, social and economic consequences), ideals (such as equality and the rights of individual citizens) and collections of data (e.g., objective, subjective)
Systemic and connective	Focusing on the relationships and patterns (including feedback and causality) that exist inside and between multilayer physical, ecological, social, and economic systems
Ethical	Expanding the scope of compassion beyond the immediate and ethical to include a feeling of ethical responsibility and a sense of solidarity with others who are not as fortunate as oneself
Purposive	Exploration of sustainable ideals and alternatives with a specific goal of aiding transformation, testing, criticism and nurturing
Inclusive and life-long	For everyone, no matter what their background or stage in life

In this day and age, the majority of universities have completed their shift to sustainability education. However, the critical question is what sort of transition occurred. Have we developed a “very strong” sustainability model, such as [Sterling and Thomas \(2006\)](#) had in mind? Or we are still far away from reaching such a model? Numerous proposals have been made on the mechanisms through which sustainability education may be integrated into higher education institutions. For example, [Dyer \(1996\)](#) and [Woods \(1994\)](#) advocate for introducing sustainability ideas and conversations into all lectures in order for students to get a holistic understanding of sustainable development in connection to their specific field, programme, and course material. As a result, integrating sustainability into the curriculum would require collaboration, rather than being the sole responsibility of a single department. In other words, each subject/course/module a student takes should add to his or her education for sustainability ([Sterling and Thomas, 2006](#)).

Currently, the creation of the course curriculum is the responsibility of academic staff who teach the student’s course. Students need, however, to be able to evaluate their own thoughts, feelings, and actions in connection to their discipline in order to be successful. Additionally, students should be aware that critical thinking, discussion, and self-reflection are necessary components of knowledge acquisition. Finally, in order to improve their critical thinking skills and provide students experience in presenting their knowledge and “understanding” ([Sterling and Thomas, 2006](#)), an interdisciplinary approach to sustainability curriculum development is needed. Many fields have unique demands, and while there are certain universal characteristics at the general level, they cannot be met by a “one-size-fits-all” approach. There should be a direct link between the education for sustainability curriculum and a particular field/discipline or profession’s problems and expectations ([Sterling and Thomas, 2006](#)).

Educating students for a sustainable future is entwined with their professional development, personal development, and graduate skills. Students are encouraged to participate in critical reflection as practitioners of sustainable development throughout their education and professional development. Through the use of a transdisciplinary approach and the transformation of the student’s learning experience, a paradigm shift will occur. This paradigm shift needs to impact not only students’ perceptions, but also academics ([Sterling and Thomas, 2006](#)).

Learning about sustainability in an engineering context is a difficult process that requires students to see the interconnectedness of many systems (Sterling and Thomas, 2006). When it comes to sustainability education, Fenner et al. (2005) suggested that students take part in problem definition and have a solid understanding of the problems, so that they can create links between the humanities, physical sciences, and technology.

Sterling and Thomas (2006) further discussed how students need to have values such as empathy for others, a desire to better the world, awareness of the environment, and a commitment to long-term growth. Students need to understand the fundamental components of ecological, social (political or cultural), or economic system interactions and connections within their discipline (or area of study), as well as principles of sustainability or sustainable development (in general and related to their discipline). In order to understand the implications for sustainable development, students must also be able to evaluate examples from their field critically within the framework of the principles of sustainable development.

2.5 Life Cycle Assessment

Sustainability education is becoming increasingly important for engineering students, as engineers are expected to play a major role in tackling the world's sustainability issues. Engineering is viewed as a critical driver of growth and innovation, and an important field for addressing the sustainability difficulties that mankind is/will be facing (Olsen et al., 2018). Engineering will be critical in achieving many of the 17 SDGs. As Olsen et al. (2018) explained, "sustainable engineering" will someday be synonymous with "excellent engineering", and sustainability education must shift from "nice to have" to "must".

When it comes to individuals and the acquisition of goods, the first factor, normally, that decides whether or not a purchase is feasible is the price. Additionally, price determines whether or not an item is considered a luxury. However, there is another sequence of decision-making processes that often goes unnoticed by customers, including: extraction of raw materials; processing; design; production; and transportation, to name a few. If a customer considers all of these hidden processes, this is referred to as [Life Cycle Thinking \(LCT\)](#). By reducing environmental impacts while boosting socio-economic performance, [LCT](#) aims to improve the sustainability of a product or system along its value chain. In other words, [LCT](#) evaluates a product's or service's environmental effects from cradle to grave, from raw material extraction through reintroduction into the ecosystem (Viere et al., 2021; UNEP, 2004; 2006). This concept underpins the environmental management technique known as [Life Cycle Assessment \(LCA\)](#).²

There has been a dramatic change over the last several decades, with legislators enacting more stringent environmental policies, consumers demanding more sustainable goods, and businesses increasingly offering sustainable products. University institutions are important in this context, especially as they are responsible for training specialists who can help with the transition towards a more sustainable society. Sustainability programs have been developed across the globe, and existing curricula have been tweaked to include sustainability concepts. A growing number of universities have begun to include the notion of [LCT](#) in their curricula. Increasingly, [LCT](#) and the accompanying [LCA](#) methodology are being taught to students (Viere et al., 2021; UNEP, 2004; 2006).

²There are more [LCT](#) tools, but for purposes of this thesis I am covering only [LCA](#). For other available tools, you can refer to [UNEP \(2004\)](#).

LCA is an analytical technique for the systematic and quantitative assessment of the environmental effects of a product or service system at every step of its life. In accordance with **LCT**, a “cradle to grave” approach is used by **LCA**. Other environmental evaluation approaches, such as “gate-to-gate” or “cradle-to-gate” embodied energy, focus only on the manufacturing phase and do not take into account the end of life ([International Organization for Standardization, 2006a;b](#)).

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by (1) compiling an inventory of relevant inputs and outputs of a product system; (2) evaluating the potential environmental impacts associated with those inputs and outputs; and (3) interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study. **LCA** studies the environmental aspects and potential impacts throughout a product’s life (i.e., cradle-to-grave) from raw material acquisition through production, use, and disposal. The general categories of environmental impacts needing consideration include resource use, human health, and ecological consequences ([International Organization for Standardization, 2006a](#)).

According to [Viere et al. \(2021\)](#), **LCA** is usually taught with an introduction to **LCT**, followed by the fundamental technique of environmental **LCA**, and then the aforementioned innovations and specialisations are taught. Future occupations may need varying degrees of **LCA** awareness. For example, individuals may merely need to grasp the value of **LCT** in analysing and managing sustainability. Others may need **LCA** literacy to comprehend and apply **LCA** findings in decision making. Others may also learn **LCA** applications to undertake full-scale **LCA** research.

Due to the multidisciplinary nature of **LCA**, it is taught at a number of levels and in a wide variety of courses, ranging from engineering to management to industrial ecology. Introduction to life cycle thinking, life cycle inventory modelling, and environmental impact assessment methodologies are among the subjects covered in **LCA** education. The usual student workload ranges from 30 hours of awareness-raising and fundamental information acquisition, to 150 hours of whole courses and modules, totalling over 360 hours of study in various areas. Not all of this work is lecture-based; the students engage with higher levels of competency, case studies, and group work as well ([Viere et al., 2021](#)).

Figure 2.5

Product life cycle adapted from *Initiative (2022)*

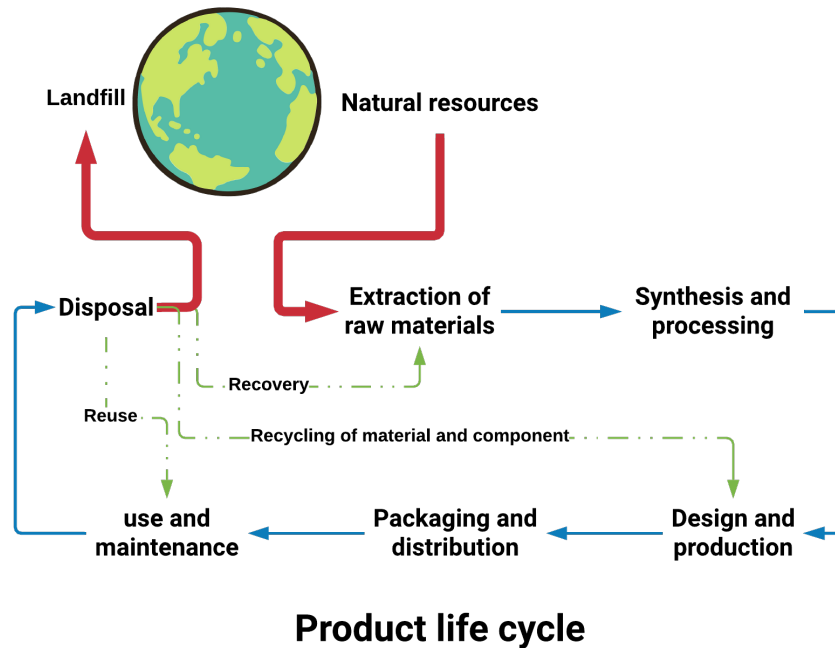


Figure note: Closed loop ecosystem and different processes that a product takes to its grave. There are alternatives to avoid a grave by implementing the three R's (Recovery, Reuse, Recycling).

2.5.1 LCA Over the Years

This section contains a considerably modified narrative of LCA's history in order to acquaint readers with this history and its evolution through time. The majority of the material in this section was derived from Guinee et al.'s (2011) "Life Cycle Assessment: Past, Present, and Future." However, because this paper was published in 2011, it was updated with new content where it was needed.

LCA can be traced all the way back to the late 1960s and early 1970s, when environmental issues such as resource and energy efficiency, pollution management, and solid waste became pressing concerns. In 1969, the Midwest Research Institute for Coca-Cola conducted one of the first (sadly unpublished) studies estimating the resource requirements, emission loadings, and trash flows of various beverage containers. A follow-up study, done by the same institute

for the United States Environmental Protection Agency in 1974, marked the beginning of the modern era of life cycle assessment. Throughout the 1970s and 1980s, [LCAs](#) were conducted using disparate methodologies and without a unified theoretical framework. There was a glaring absence of worldwide scientific platforms for [LCA](#) discussion and sharing. Firms have also regularly used [LCA](#) to substantiate market claims. The obtained results varied significantly, even when the studies' objectives were same ([Guinee et al., 2011](#); [Reddy et al., 2019](#)).

The 1990s saw a phenomenal increase in scientific and coordinating activity on a global scale. Along with [Society of Environmental Toxicology and Chemistry \(SETAC\)](#), the International [International Organization for Standardization \(ISO\)](#) has been engaged in [LCA](#) since 1994. [ISO](#) was formally charged with the responsibility of standardising techniques and processes ([Guinee et al., 2011](#); [Reddy et al., 2019](#)). At the moment, two international standards exist:

1. [ISO 14040 \(2006\)](#), "Environmental management: Life cycle assessment - Principles and framework"([International Organization for Standardization, 2006a](#))
2. [ISO 14046 \(2006\)](#), "Environmental management: Life cycle assessment - Requirements and guidance" ([International Organization for Standardization, 2006b](#))

[United Nations Environment Programme \(UNEP\)](#) and [SETAC](#) created the Life Cycle Initiative, an international life cycle partnership, in 2002. [LCT](#) has continued to gain prominence in European policy, as seen by the European Commission's Communication on Integrated Product Policy. The European Platform for [LCA](#) was founded in 2005. In the United States of America, the Environmental Protection Agency began promoting the use of [LCA](#) ([Guinee et al., 2011](#); [Reddy et al., 2019](#)).

2.5.2 LCA in Engineering Education

[LCA](#) is utilised as a teaching strategy in higher education to assist students to learn about and apply the sustainability framework. According to [Olsen et al. \(2018\)](#), the primary learning outcomes that can be attained through [LCA](#) in higher

education include, but are not limited to: defining key elements of sustainability; quantitative assessment of the environmental life cycle; and sustainability in business and management. This list of learning outcomes is not comprehensive.

Students who want to become technology leaders (generalists) or sustainability experts (specialists) need different degrees of competency. Table 2.4 by [Olsen et al. \(2018\)](#) shows that the courses offer a variety of options for each of the learning goals. Table 2.4 summarises what is involved in reaching bachelor level skill; the extended Table published by [Olsen et al. \(2018\)](#) covers masters and PhD levels as well. As a result of this process, students who aim to become sustainability professionals are given the opportunity to learn about the various aspects of sustainability, from a very basic level. Each course's learning outcomes are used to measure students' progress towards the overall learning objective.

Table 2.4

Teaching strategy of quantitative sustainability for engineers adapted from Olsen et al. (2018). Each objective is assigned with appropriate Bloom's Taxonomy and learning competences

Main learning objectives	Bloom's Taxonomy	Main acquired competences	Teaching methods
Understanding environmental sustainability	Bloom's level 1	Recognize sustainability challenges and engineer's role in achieving or improving environmental sustainability	Lecture and group discussion
Comprehend LCA concepts Apply to and analyse simple civil engineering system	Bloom's levels 1-3	Identification and optimization of resource consumption and environmental impacts for civil engineering projects	Lectures and exercises
Comprehend LCA and eco-design concepts Apply to and analyse simple civil engineering systems	Bloom's levels 1-4	Quantification and analysis of environmental impacts from buildings, components and products eco-design (synthesis-oriented)	Lectures and exercises
Comprehend companies' work with corporate social and environmental responsibility (CSR) Elaborate on a corporate carbon footprint	Bloom's levels 2-6	Knowledge and capabilities regarding CSR and corporate carbon footprint	Lectures and case project-based group work
Comprehend and analyse sustainability from a life cycle perspective	Bloom's levels 1-6	Assessing sustainability using simple methods and synthesize new solutions	Lectures and case project (real life) based group work

Malkki and Alanne (2017) argued that, in order for students to understand the components of sustainability in complex systems, students require a framework that is systemic in nature and contains systemic concepts and procedures. For sustainability to be taught effectively, educators require a framework that prompts students to think critically about a broad range of issues related to sustainability. LCT is the best framework available that can help educate students about sustainability and LCA (Malkki and Alanne, 2017). The purpose of LCT is to evaluate a product's impact on the environment, on people's lives, and on the economy at every stage of its production and use. The process starts with conceptualization and continues through to final disposal and recycling. The information gleaned from these evaluations can be put to use in a number of ways, including the creation of a more well-rounded product or the conduct of a comparative analysis of the market (Naumann et al., 2011).

Several competences and learning outcomes for LCA and LCT instruction in engineering education have already been provided in Table 2.4. Olsen et al.'s 2018 comprehensive vision for incorporating sustainability education into engineering curricula encompasses a wide range of aims, from resource optimization to environmental protection, and from sustainability for engineering designs, to LCA for products and systems, to advanced system modelling using LCA, to, most importantly, the impact of engineers on people's health and well-being. Furthermore, the significance of LCA as a teaching tool for environmental awareness has been discussed (Strobel et al., 2010; Weber et al., 2011). There have been several applications of the LCA since it was first developed, including energy and chemistry; food and agriculture; engineering; and many other fields (Strobel et al., 2010; 2009; Piekarski et al., 2019; Yang et al., 2020; Weber et al., 2011).

LCA was also nominated as a threshold concept by Strobel et al. (2010) and Weber et al. (2011). They found that LCA may be used to educate engineering students about environmental issues. Strobel et al. (2010) proposed four primary domains as possible threshold concepts for beginning engineering students. The majority of the domains consisted of measurements and procedures where students had trouble with unit measures and environmental impact-related physical quantities, or struggled with the use and utilisation of LCA in day-to-day living.

The majority of Weber et al.'s (2011) threshold concepts were connected to Strobel et al.'s (2010) research in the sense that they incorporated students' full comprehension of LCA and the engineering application of LCA. In Strobel et al.'s (2010) original research, they were unable to determine whether threshold concept(s) in LCA could increase students' comprehension of LCA. However, Weber et al.'s (2011) study demonstrated that students' grasp of environmental sustainability and LCA could be enhanced by concentrating on threshold concepts in LCA. Weber et al. (2011) focuses on aspects of LCA that have caused students difficulty, such as broad concepts that are unrelated to their disciplines, difficulty acquiring data and obtaining the correct result, conflicting feelings about a product's functionality and being environmentally friendly, and, most importantly, complexity and uncertainty within LCA as the top threshold concept.

LCA's complexity and unpredictability are affected by its reliance on data from a variety of regions, distinct unit operations, a vast array of sources, data that is usually not gathered for LCA aims, and more or less subjective methodological decisions. In most scenarios, the results of an LCA are presented as estimates and assumptions (Bjorklund, 2002).

Bjorklund (2002) mentioned that uncertainty in LCA is caused by not knowing the actual value of a quantity. The term "uncertainty" used in a LCA context refers to both unknowns and variations, and also includes additional, non-quantitative aspects that influence the accuracy of LCA models. As such, Bjorklund (2002) identified several varieties of uncertainty in LCA models, including: data inaccuracy³, Data gaps⁴; unrepresentative data⁵; model simplification⁶; and uncertainty due to choice⁷.

Reap et al. (2008) also confirms Bjorklund's (2002) assessment of what causes problems in LCA, as illustrated in Table 2.5. Reap et al. (2008) additionally identify challenging elements within each phase of LCA. For example, functional unit and system boundary have been identified as challenging steps in goal and scope phase.⁸ It is possible to avoid most of the challenges after goal and scope

³The precision of the measurements used to produce the numerical parameter values is at the heart of the issue of data inaccuracy.

⁴The parameters are missing values.

⁵similar data but usually not from same process or region.

⁶too simplified model with missing steps.

⁷Uncertainty in selecting important parameters, such as allocation rules, functional units, system boundaries, characterization approaches, and weighting schemes.

⁸See Section 2.5.3 for more information.

Table 2.5*Most frequent problematic qualities of LCA*

Phase	Problem
Goal and scope definition	Functional unit definition
	Boundary selection
	Social and economic impacts
	Alternative scenario considerations
Life cycle inventory analysis	Allocation
	Cut-off criteria
	Local technical uniqueness
Life cycle impact assessment	Impact category and methodology
	Spatial variation
	Local environmental uniqueness
	Dynamics of the environment
Life cycle interpretation	Time horizons
	Weighting and valuation
All stages	Uncertainty in the decision process
	Data availability and quality

section by planning the study in advance. However, the data gap and uncertainty suggested by [Bjorklund \(2002\)](#) can influence the study result, which itself causes stress for students.

According to [Lloyd and Ries \(2007\)](#) uncertainties reported in each study will tend to be subjective. The complex nature of [LCA](#), as well as the lack of consistency in methodological steps by [ISO](#), permits everyone to conduct [LCA](#) in their own way. This situation has created a common expectation of encountering uncertainties in most [LCA](#) studies ([Reap et al., 2008](#)). [Lloyd and Ries \(2007\)](#) further mentioned that the complexity of [LCA](#) impedes a common solution, and therefore each [LCA](#) study has its own method of fighting uncertainty. [Lloyd and Ries \(2007\)](#) emphasised how expert knowledge and experience is the only sure means to mitigate the influence of uncertainty on study results. That is why [Weber et al. \(2011\)](#) introduced uncertainty as one of [LCA](#)'s threshold concepts.

2.5.3 LCA Framework

The [International Organization for Standardization \(ISO\)](#) specifies four processes in its [LCA](#) methodology: goal and scope definition; inventory analysis; impact assessment; and interpretation. In the first phase, the rationale for doing the [LCA](#) research is addressed. The second phase, dubbed life cycle inventory analysis, involves compiling a list of all flows from and to natural environments over the course of a system's life. Natural flows or inputs may include water, energy, and raw materials. On the other side, flows to natural environments include discharges into water, air, and land. At the conclusion of this step, a list of resource flows into and out of the system in question is created. The third step, impact assessment, is likely the most difficult aspect of an [LCA](#) research ([Gundes, 2016](#)). Since it evaluates the magnitude of environmental consequences identified during the inventory analysis.

The multi-step approach begins by classifying impacts into areas such as climate change, land use, acidification, toxicity, and ozone depletion. The preceding phase's outcomes are then classified according to their impact (e.g., CO₂ emissions from the system are assigned to the climate change category). At this stage, it is necessary to characterise indicators in order to compare findings presented in various units within each effect category. Finally, in the interpretation phase of the [LCA](#), the results are examined, conclusions are given, limits are highlighted, and suggestions are made ([Gundes, 2016](#); [International Organization for Standardization, 2006a;b](#)).

The next section will provide a short summary of [LCA](#) framework stages. The reference for this section is Baumann and Tillman's (2004) *The Hitch Hiker's Guide to LCA*, a smart and well-respected book on the subject of life cycle assessment.

Goal and Scope

In the goal and scope stage, the product to be investigated and the purpose of the study are determined. According to the [International Organization for Standardization \(2006a\)](#) the goal description comprises identifying the intended application of the study, the purpose for carrying it out and to whom the findings are meant to be conveyed. The guideline undercores that the goal and scope of an [LCA](#) study must be clearly stated and compatible with the intended application.

Figure 2.6

LCA methodology diagrams as presented by the *International Organization for Standardization (2006a)*

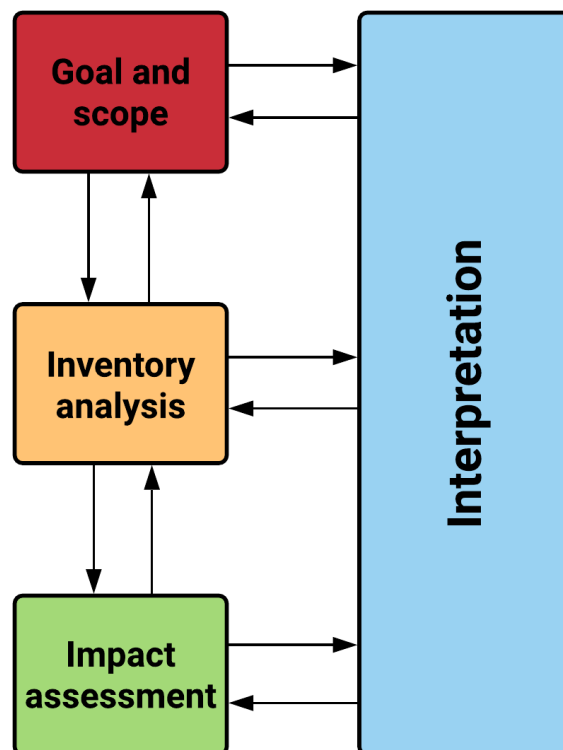


Figure note: In this diagram each stage has a direct relationship with the next and there is not a fixed path to follow. At any stage new information could be added to improve the study; therefore, authors are required to always double check their data at any stage.

According to [Baumann and Tillman \(2004\)](#), when an LCA study is undertaken, the aim is typically described very generically and broadly. Initially it may be phrased as “We want to perform an LCA on our product” or “We want to illustrate the environmental benefits of our product”. However, before an LCA can be performed, the problem formulation (research question) has to be described more explicitly. Furthermore, the context of the research is established, for example to whom and how the findings are to be presented. Specifications of the modelling to be performed are also developed and the project is planned.

One example of such a modelling specification, and one of the most important choices in the LCA study, is the choice of functional unit. LCA ties environmental effect to a product, or rather to the function of a product system. Thus, there

is a requirement to represent the function in quantitative terms, as a functional unit. [Reap et al. \(2008\)](#) defined a functional unit as "...a measure of the performance of the functional outputs of the product system....to provide a reference to which the inputs and outputs are related. . . [and]... to ensure comparability of LCA results." Examples of functional units as suggested by [Baumann and Tillman \(2004\)](#) include beverage packaging (litres of packed drinks) and passenger transportation (person per km).

When two similar products are being compared based on their function (transportation), it is vital to choose the same functional units throughout the study to guarantee that the study is done fairly and precisely. The difference in function and functional unit might influence the study's reliability. Many more decisions relating to the modelling are made during the goal and scope definition. They are listed below, with selected examples further explained.

- What procedures should be included in the system? The selections of what to research are chosen during the goal and scope definition stage, and control the system limits of the flow model constructed in the following inventory analysis.
- Possible effects on the environment. Most LCAs take into account a standard set of consequences, such as resource usage, global warming, acidification, and eutrophication, although some LCAs evaluate only a subset of these effects. The parameters for data collection during inventory analysis are determined by the selected effects.
- The level of detail in the investigation, and consequently the data required.

Inventory analysis

Life Cycle Inventory (LCI) entails creating a systems model based on the requirements of the goal and scope description. The systems model is a flow diagram of a technological system with specific system boundaries. As a consequence, the system has an imperfect mass and energy balance. Only the environmentally significant flows are given detailed consideration in this stage. This is also known as an initial LCI flowchart, and it helps with finishing the system boundary selection. [Baumann and Tillman \(2004\)](#) briefly describe the LCI stage as follows:

- The flow model is built in accordance with the system boundaries specified in the goal and scope description. The flow model is often represented as a flowchart that depicts the activities involved in the system under consideration (production, processing, transportation, usage, and waste management) as well as the flows between the activities.
- Data gathering for all product system operations (processes and transfers). The information gathered comprises the inputs and outputs of all operations, such as raw materials, energy consumption, solid waste, and emissions into the atmosphere and water.
- Calculation of the system's consumption of resources and pollutant emissions in relation to the functional unit.

Even though the [LCI](#) seems to be simple, there are many hidden processes and emissions that are generally not discovered until the complete flow chart of the system/product is reviewed. There are several methods to cope with these issues, and [International Organization for Standardization \(2006a\)](#) has offered guidelines on how to do so. Multiple products produced from the same resource input is the most typical allocation problem in an [LCA](#) study. We will not go into these approaches in detail in this thesis, since the purpose of this section is to expose the reader to the fundamentals of LCA. Please see [Baumann and Tillman \(2004\)](#) for further information on [LCI](#) and dealing with [LCA](#) allocation.

Impact Assessment

The goal of [Life Cycle Impact Assessment \(LCIA\)](#) is to explain, or at the very least highlight, the implications of the environmental loads quantified in the inventory analysis. One goal of the [LCIA](#) is to convert the inventory data into more environmentally relevant information so that the reader can follow the effects in more familiar terms, rather than, for example, using tables and figures with names of gases that the typical reader would not understand. Another goal, albeit less often expressed, is to condense the data from the [LCI](#) into fewer parameters.

The first stage of [LCIA](#) is classification, which basically involves categorising inventory characteristics based on the kind of environmental effect they have. The proportionate contributions of emissions and resource consumption to each

category of environmental effect are estimated in the next step: characterisation. For example, all greenhouse gas emissions may be aggregated into a single indication for global warming, and all acidifying emissions could be aggregated into a single indicator for acidification. These estimates are based on scientific models of natural system cause-and-effect chains.

In its most basic form, the [LCIA](#) aids in the conversion of all data from previous phases into figures that are easy to read and analyse, since these data are eventually utilised to write an executive summary, as well as in reports comparing and selecting the least environmentally damaging option. The existing software on the market may help with this stage, since it has all of the environmental data needed to complete the [LCIA](#) classification and characterisation procedures.

Interpretation

After the inventory computations, the number of output parameters might easily exceed a hundred. There are a lot of numbers, and it may not be simple to comprehend them all at once. In order to extract something meaningful out of the numbers, it is necessary to “refine” the raw results in some way. Raw data must be refined into usable, presentable, and final data via a process that may include screening the raw data, identifying key data, and assessing the value of missing data. In [LCA](#) terminology, interpretation refers to the process of analysing findings and drawing conclusions.

The term “life cycle interpretation” is defined in the ISO 14040 standard as the “phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistent with the defined goal and scope in order to reach conclusions and recommendations” ([International Organization for Standardization, 2006a](#)). Various forms of diagrams come in use throughout this procedure. The interpretation phase also includes assessments on the solidity of results generated from an [LCA](#) research. Data quality and sensitivity assessments are common components of these types of studies.

2.6 Statement of Research Questions

This study was framed by the following research question after examining the gaps in the literature and in order to meet the purpose of my research. The answers to each question, I believe, will be valuable to the domains of sustainability and engineering. Lastly, establishing a framework for a broader understanding of threshold concepts for all engineering disciplines was required, thus the broad reach of the questions.

Main question: How do student perspectives on sustainability influence students' understanding of threshold concepts in sustainability engineering education?

Supporting questions:

- What are the threshold concepts in sustainability for engineering disciplines?
- Are threshold concepts in sustainable engineering common across disciplines?
- How do students perceive sustainability?

2.7 Chapter Summary

This chapter has offered a review of the literature pertinent to the research questions underlying this study. The evaluated literature contains concepts linked to sustainability, TCT, engineering education, and essential sustainability skills, as well as LCA as the most popular topic in sustainability education taught to engineering students. It was discovered that student perceptions have a significant impact on learning. Most key competencies in sustainability education place a high value on students' perceptions and encourage teachers to make the curriculum relevant to students' disciplines. This is because, when students are able to make connections between the sustainability lessons and their own field of study, they are more likely to retain the information.

After conducting a thorough literature review, it has become evident that there is a pressing need for additional research aimed at identifying sustainability threshold concepts specific to engineering students. While the literature has identified a number of threshold concepts that are applicable to various disciplines, it is essential to determine which of these concepts are most relevant to the field of engineering. Furthermore, it is crucial to investigate the pedagogical methods that are most effective in facilitating student learning in this area. Thus, it is clear that further research is required to fully comprehend the sustainability threshold concepts that are most significant for engineering students, and to develop the necessary teaching strategies to help students grasp this crucial material.

In the upcoming chapter, the study's research methodology and methods will be outlined. This will encompass an explanation of the research design, as well as the procedures for collecting and analyzing data.

Chapter 3

Methodology and Methods

3.1 Chapter Overview

This research is a mixed-method study that adopts an [interpretivist](#) theoretical perspective and [Threshold Concept Theory \(TCT\)](#) to identify the threshold concept(s) in sustainable engineering. This study employed [phenomography](#) to study the many perspectives that arise from students' and lecturers' experiences. [Interpretivism](#) and [phenomography](#) enabled the study to interpret how students' and lecturers' perspectives were shaped by sustainability.

Research projects set their goals based on the paradigm they employ ([Glesne, 2016](#); [Mackenzie and Knipe, 2006](#)). A research paradigm is a "loose collection of logically related assumptions, concepts, or positions that orient thinking and research" ([Bogdan and Biklen, 2007](#), p. 24). The [epistemology](#), [theoretical framework](#), [methodology](#), and [methods](#) employed in this study will be laid out in detail first, as each are reliant on one another to determine the conduct of an investigation ([Creswell and Clark, 2017](#); [Crotty, 1998](#); [Glesne, 2016](#)).

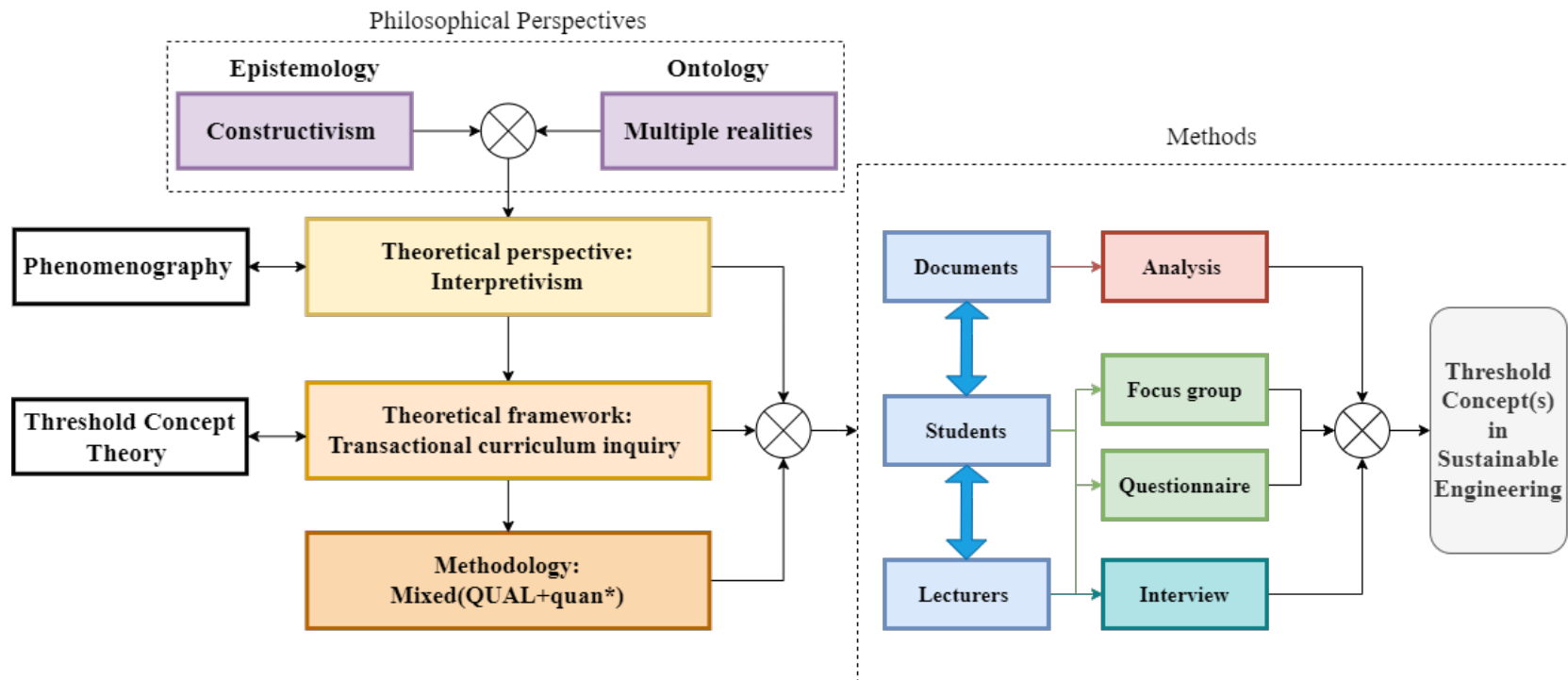
The methods selected were led by the methodology chosen, which in turn was shaped by the theoretical views of the study, which were themselves impacted by the researcher's epistemological stance. [Figure 3.1](#) illustrates an overview of the research design. This study draws on [Crotty's \(1998\)](#) model, also used by [Creswell and Clark \(2017\)](#). [Crotty \(1998\)](#) argues that mixing all terminologies

together is confusing; therefore, he represents terms such as [epistemology](#), [ontology](#), theoretical perspective, methodology, and methods as distinct levels of decision making for research design.

This chapter includes an overview of educational research paradigms, and the research design used in this study. There is also a discussion of the study's data [collection methods](#) and [methodology](#). Primary data sources for this study include individual and focus group interviews, questionnaires, and secondary data such as student assignments. The research's [reliability](#), [validity](#), [ethical concerns](#), and sampling techniques are also examined. The chapter concludes with identification of the framework that will be used to organise the study's findings in the [discussion chapter](#).

Figure 3.1

Overview of research design



**QUAL" stands for qualitative and "quan" stands for quantitative. Capital letters indicate the higher weight, and lower case letters indicate the lower weight

Figure note: This mixed-methods study uses Cousin's (2009) theoretical framework to identify possible threshold concept(s) in sustainable engineering. Therefore, the methods utilised in this study were chosen based on [Transactional Curriculum Inquiry](#), which is also known as Threshold Concept Theory research.

3.2 Philosophical Perspectives

The two most important philosophical concepts that are used to define different research paradigms are [ontology](#) and [epistemology](#) ([Schneeg, 2014](#); [Wahyuni, 2012](#)). [Ontology](#) and epistemology aid the researcher to adopt a particular stance toward the nature of knowledge, as well as the role of the researcher and research ([Wahyuni, 2012](#)). Ontology is the study of being, and it can be framed as a question: “what is the form and nature of reality” ([Guba and Lincoln, 1994](#), p. 108). Epistemology is “how we know what we know” ([Crotty, 1998](#), p. 8), or, as [Guba and Lincoln \(1994, p. 108\)](#) framed it, “what is the nature of the relationship between knower and knowable?” Epistemology is used to provide a philosophical grounding for validating our understanding ([Cohen et al., 2017](#)). It is widely accepted that the principles and assumptions of philosophical ideas underlie every research investigation, irrespective of whether the investigator explicitly acknowledges them ([Neuman, 2011](#)). However, by keeping in mind the fundamental principles and premises of ontology and epistemology, researchers may enhance their comprehension of the options available to them throughout their work ([Glesne, 2016](#)).

3.2.1 Ontology

There are many ways to conceptualise reality, and [Crotty \(1998\)](#) describes two general ontological stances, realism and nominalism. For the realists, the universe exists whether humans act or not, and the way the world is organised is already built into pre-existing categories, waiting to be discovered ([Neuman, 2011](#)). Nominalists believe that people can never completely pull away the interpretive lens through which they see the world, but they also argue that certain interpretative schemes are more opaque than others ([Neuman, 2011](#), p. 92).

This research uses a nominalist stance, asserting that social and physical human experience are interpretive and cultural in nature ([Neuman, 2011](#)). There are multiple realities, and contextual realities can socially explain the nature of an individual’s perspective. Based on these facts and their lived experiences, each participant’s perspective is regarded as potentially unique ([Creswell and Clark, 2017](#)). Each participant imparts meaning uniquely, resulting in the creation of

numerous worlds. Even when two people face the identical surrounding circumstances, their perspectives are acknowledged to be distinct. Even though two participants may have had the same experience from the perspective of an interpretive and naturalistic researcher, their perspectives were observed and evaluated differently. This research sought to elucidate each participant's created world.

3.2.2 Epistemology

There are two primary reasons why the epistemological perspective is important. According to [Gray \(2017\)](#), understanding conceptual ideas is the first step to deciding on the best research methodologies to achieve a researcher's goals. Another consideration is the enquiry design, namely how the study will be organised and how evidence will be gathered and evaluated. [Crotty \(1998\)](#) argues that three epistemic perspectives exist: objectivism; subjectivism; and constructionism. Objectivist epistemology claims that meaning exists whether or not there is human awareness, and that knowledge is discoverable. This concept of meaning only works when the object is involved. However, subjective epistemology asserts that the object is unimportant for constructing meaning, and that meaning is instead created by the subject.

Constructionism emphasizes that knowledge does not exist to be discovered, but it is constructed by the individual's interaction with the world ([Gray, 2017](#); [Guba and Lincoln, 1994](#); [Schwandt, 1994](#)). [Creswell and Clark \(2017, p. 36\)](#) introduce constructionism as "the understanding or meaning of phenomena, formed through participants and their subjective views". The participants will talk from their perspective and personal history; therefore this research will be 'bottom-up', structured from the participant's perspective, and will build inductively to a broad understanding ([Cohen et al., 2017](#); [Creswell and Clark, 2017](#); [Gray, 2017](#)).

[Crotty \(1998\)](#) explains how constructionism rejects the notion that human knowledge is made up of concepts. We can't find a truth that doesn't exist. The reality of our world gives rise to truth and meaning, which exist within and outside of our interactions with it. A mind means nothing without purpose. Finding meaning isn't like discovering a hidden treasure; it's more like manufacturing it. A good grasp of knowledge helps us realise that individuals interpret distinct concepts

in various ways, even if they are describing the same phenomenon. In this interpretation, subject and object are co-creators of meaning. We can utilise *Star Wars* films to better grasp constructionism. Obi-Wan Kenobi and a number of other Jedi are constructionism archetypes, although they sometimes veer into the post-positivist. Obi-Wan Kenobi cherishes logic, but he is also a human being who is acutely aware of the value of context. He recognises that meaning is formed between cultures and people, as well as the dual nature of the world. There are many shades of grey that arise in the human realm (Norman, 2019).

Constructionism opposes both objectivist and subjectivist perspectives, arguing that meaning cannot be completely described in objective or subjective terms (Crotty, 1998). According to constructionism, meaning is produced via interactions between the subject and the object (Crotty, 1998). There is no meaning without the mind since meaning is constructed rather than found.

My epistemological stance is that knowledge is not 'discovered', but instead created with the knower's experience (Guba and Lincoln, 1994; Lincoln and Guba, 2013). Meaning can be created in a variety of ways, even when it comes to the same concept. Therefore, multiple conflicting, but equally valid, explanations of the same concept are possible with constructionist epistemology (Gray, 2017, p. 20). Because this research is about students who create meaning in a variety of ways and in a variety of different backgrounds, the constructionist epistemology was considered most applicable.

3.3 Theoretical Perspective

The theoretical perspective is a philosophical position that enables the researcher to choose a range of methodologies which, in turn, points to the appropriate research design, data gathering, and analysis (Crotty, 1998). The theoretical perspective as outlined by Crotty (1998) is a method of seeing and making sense of the world. Thus, it entails knowledge and contains a certain notion of what it is to know, that is, how we know what we know. Research is usually based on the researcher's 'world-view', also known as paradigm (philosophical perspective), which guides the researcher's point of view about the world (Creswell, 2012).

A research paradigm is a set of ideas or agreements, recognized by researchers, that define how to comprehend and address problems (Johnson and Christensen,

2012). It may be described as the structure and alignment of researchers' thought that shapes their world-view and research behaviour (Jonker and Pennink, 2010; Punch and Oancea, 2014). Positivism, interpretivism and critical theory are the most common paradigms in educational research (Cohen et al., 2017).

The positivist paradigm is a realist and determinist perspective that regards social reality as ontologically objective (Crotty, 1998). The current research, however, is incompatible with a positivist paradigm since, in order to identify threshold concept(s) of sustainability among multiple engineering disciplines, it was required to ask participants about their perspectives, experiences, and attitudes about sustainability. As a result, participants' subjective world-views are critical in locating these threshold concepts in sustainability engineering. Accordingly, the interpretivism paradigm is used in this study (Creswell and Clark, 2017). The underlying assumptions of this study deny positivist cause and effect correlations between things. Because I was interested in the subjective experiences of students and lecturers within their discipline, positivism did not appear to be the appropriate paradigm for use in this study. Positivist researchers believe that objective approaches can be utilised to investigate social issues in social research. As a result, they often employ quantitative data from experiments, examinations, and observations (Cohen et al., 2017). However, in this study, I was particularly interested in students' perspectives, perceptions, and experiences.

Critical theory did not appear to be consistent with the study's objectives and methodologies. The critical theory method attempts to challenge the principles and existing practices of students and instructors (Cohen et al., 2017). This study, however, had no intention of influencing participants' behaviour. An interpretivist approach is one that focuses on the interpretations individuals make of situations and behaviours (Punch and Oancea, 2014). Interpretivist research views reality as diverse and socially created, and emphasises the importance of experiences and social interaction (Crotty, 1998; Wahyuni, 2012). Interpretivist research was chosen as the suitable theoretical perspective for this study due to its emphasis on individuals' subjective perceptions of the world. In an interpretivist framework, social reality is seen as subjective (Crotty, 1998; Wahyuni, 2012), and reality is shaped by social actors and individual perspectives (Cohen et al., 2017). As a result, interpretivist scholars may distinguish between different realities (Guba and Lincoln, 1994). The purpose of this research was

to identify threshold concept(s) in sustainability for different disciplines of engineering with the help of participants' experience. Because interpretivism takes into consideration people's experiences, it is deemed a suitable paradigm for this study.

3.3.1 Interpretivism

The interpretivist paradigm is used by researchers to try to comprehend the subjective realm of human experience (Cohen et al., 2017). The researcher's perspectives are deemed critical in this paradigm. To maintain the study's integrity, the researcher makes an effort to comprehend the participants from the inside out (Cohen et al., 2017). Crotty (1998) asserts that people must be understood in connection to their culture, since individuals are believed to be affected by other people, places, and objects in their environment. Given that the interpretivist paradigm is concerned with participants and their interpretations of the world around them (Crotty (1998), this study placed an emphasis on understanding participants' understanding, interpretations, and actions within their discipline of engineering.

The primary objective of this study was to identify threshold concepts in sustainability. Epistemologically, this research constructed knowledge by examining each participant's experiences and perspective on the sustainability of their discipline. This study sought to distinguish, not only the participants' views and experiences, but also to demonstrate universal threshold concepts across all fields. This approach was regarded as closely linked with a phenomenographic approach, since it aimed to "to characterize variation in people's experiences" (Richardson, 1999, p. 64), rather than to describe different individual experiences. Thus, while each participant has diverse perspectives and experiences of sustainability in their discipline, phenomenography provides a way of looking at their experiences collectively and holistically (Akerlind, 2005).

Knowledge is relational, formed via interactions and connections between individuals (subjects) and the world (object) (Marton, 2000; Marton and Pang, 2008), and it is comprehended through the many interpretations of phenomena connected with people's experiences (Marton, 2000). As a result, experiences are acquired interactively via social interactions and are contingent on both individuals and the environment. Thus, witnessing a phenomenon is the only way

to comprehend its actuality (Marton, 2000). By adopting a second-order viewpoint, a researcher has access to many facets of reality through other people's experiences (Marton, 1981).

Phenomenography

Phenomenography is an approach within qualitative research that falls within the interpretivist paradigm. Its objective is to investigate the various conceptions of a certain phenomenon that emerge from people's experiences. Phenomenography is used for "mapping the qualitatively different ways in which people experience, conceptualise, perceive, and understand various aspects of, and phenomena in, the world around them" (Marton, 1986, p. 31).

Its non-dualistic, ontological perspective investigates the notion that individuals see the world differently depending on their circumstances; that is why it is both "objective and subjective" (Marton, 2000, p. 105). This non-dualist ontological perspective influences its epistemological position (Marton and Pang, 2008), which is described as "an internal relationship between human beings and the world" (Pang, 2003, p. 145).

The phenomenographic perspective differentiates itself from phenomenology in educational research by concentrating on respondents' experiences. Phenomenographic research focuses on the participants' relationship to the phenomena, rather than the researcher's. Despite some similarities, conflicts between phenomenography and phenomenology exist due to their aims within a single study. While phenomenology attempts to identify the nature of phenomena, phenomenography is a technique for understanding people's perceptions and experiences of these phenomena (Marton, 1981; Stamouli and Huggard, 2007). Phenomenology tries to understand the phenomena via researcher observation, while phenomenography attempts to learn about the phenomena through questioning participants' views (Marton, 1981). In distinguishing the 'first-order' and 'second-order' perspectives, Marton (1981, p. 171) noted that the first-order perspective for a researcher means being "from the outside" and the second-order perspective means being "from the inside".

3.4 Theoretical Frameworks: Transactional Curriculum Inquiry

Cousin (2009) presented the theories relating to TCT research, which may assist researchers in identifying threshold concepts in any discipline. Cousin introduced Transactional Curriculum Inquiry also known as Researching Threshold Concept to help researchers identify threshold concept within the discipline under study. TCT is the curriculum's "jewels" (Meyer and Land, 2005). The emphasis on the obstacles to mastery in the subject is a primary draw of threshold concept research. Typically, this approach necessitates collaboration between subject specialists, researchers, and students. The fact that threshold concept research addresses curriculum inquiry and curriculum design as concurrent, rather than sequential, activity adds to its attractiveness (Cousin, 2009).

TCT research is undertaken to distinguish difficulties regarding either teaching or learning a particular subject and to support the curriculum design process (Cousin, 2009). The assumption that kickstarts the research is that any subject has several concepts which students find hard to understand (Meyer et al., 2016). TCT research does not adhere to a specific method of inquiry; instead, it provides an analytic framework to identify conceptual and (sometimes) emotional challenges within the discipline. What makes TCT stand out is the possibility that, if mastered, it will alter a learner's cognitive resources and identity (Cousin, 2009; Rattray, 2016).

Research design centred on the participants' knowledge and attitude towards sustainability is needed to identify threshold concepts of sustainability among multidisciplinary engineering students. This research employs TCT as a theoretical framework; however, to prevent misunderstanding, it will be referred to as Transactional Curriculum Inquiry in order to present a fuller picture of threshold concepts of sustainability in engineering and students' perspectives on TCT and sustainability. Regardless, the study was informed by Cousin's (2009) suggestions and recommendations for researching threshold concepts.

3.5 Methodology

Taking into account the [ontological](#) and [epistemological](#) views, and in alignment with the research goals, the study was structured as a mixed methods study comprised of three phases (Figure 3.3), each of which included distinct steps. Both quantitative and qualitative data were analysed and merged in this study to identify threshold concepts as a component of sustainability for multi-discipline sustainable engineering.

This research was undertaken during the first phase of COVID-19, and as a consequence, the original study methodology was significantly altered. The research was initially planned to be split into two phases, with the second phase serving as a largely quantitative investigation. To address the study questions, the idea was to take the first phase data and perform significantly larger surveys. However, as will be explained further in the ethical considerations section, due to COVID lockdown the study invitation, which was sent out across two universities, did not get enough responses. As a result, the third phase was implemented as a precautionary step to ensure that the study's reliability remained unaffected by the pandemic. The study's overall structure was not significantly altered by the revisions made. The main drawbacks were a paucity of data and a two-year delay that impacted publication and research output.

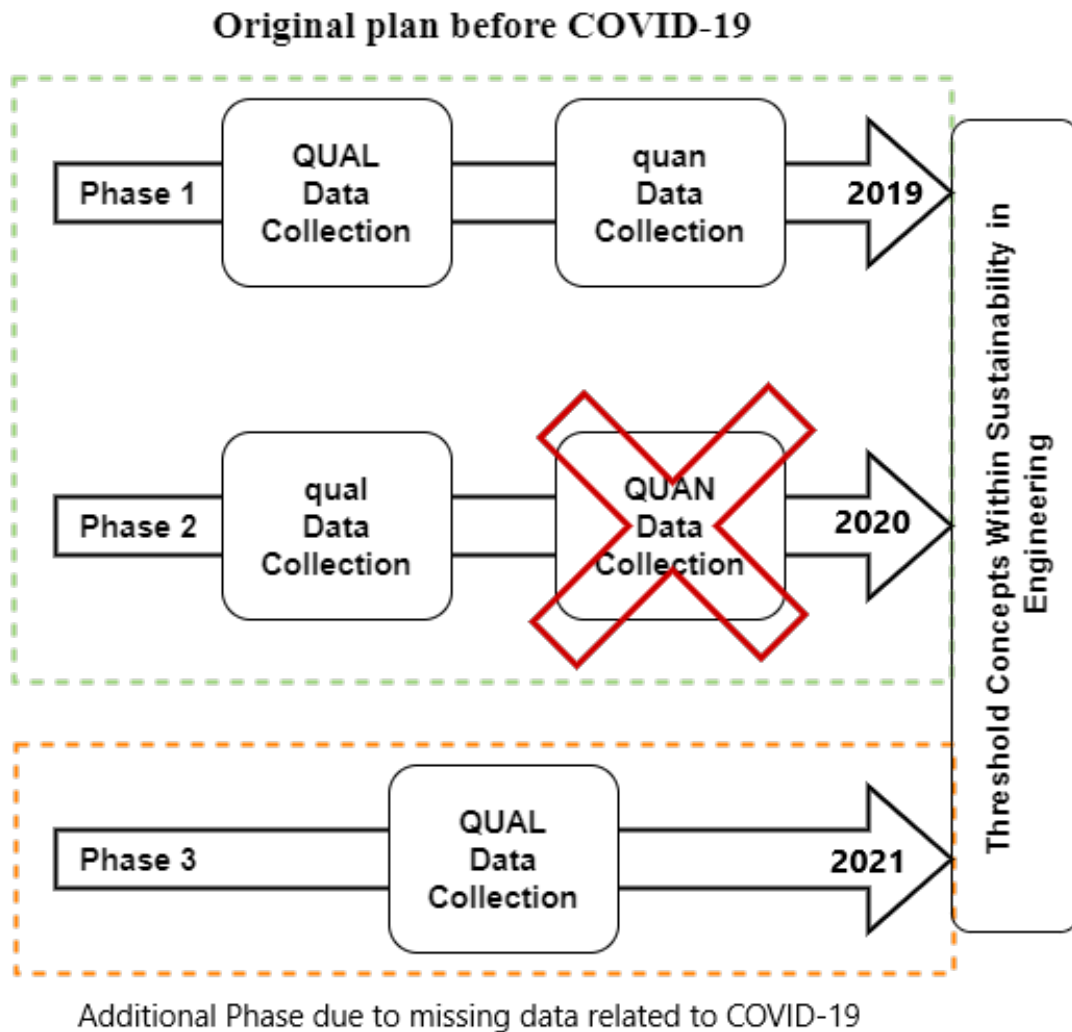
Mixed methods research is a research method which systematically integrates quantitative and qualitative data within a single investigation ([Creswell and Creswell, 2018](#)). By integrating the qualitative and quantitative data, the research process under study may be better understood by seeing it through an improved lens ([Creswell and Creswell, 2018](#)). The first advantage of mixed methods research is that it provides a deeper knowledge of the process than can be obtained via either qualitative or quantitative techniques alone, and may provide a broader and more comprehensive answer to the research question. Moreover, it promotes the idea of complementarity, meaning that the strength of one technique balances out the other method's deficiency ([Malina et al., 2011](#); [Gray, 2017](#)). The first drawback of mixed methods research is that the overall design is potentially complicated and, when compared to other techniques, more costly and time-consuming. It may also be difficult to apply one approach based on the results of another approach ([Malina et al., 2011](#); [Creswell and Clark, 2017](#)).

There was a limited time to collect the data from participants, and both quantitative and qualitative data from every participant was needed to identify threshold concepts of sustainable engineering. Therefore, [Creswell and Clark \(2017\)](#) and [Creswell and Creswell's \(2018\)](#) convergent design was adapted in this study. Convergent design is a mixed-methods approach in which the researcher gathers and examines two databases, quantitative and qualitative, before merging them to compare or combine the findings. This design offers a variety of advantages and benefits. It is a time-efficient approach in which both kinds of data are gathered within the same period of the study. Each kind of data may be gathered and evaluated individually, using the methods that have historically been associated with it. The approach enables direct comparison of participants' views collected via open-ended data collection (e.g., semi-structured interview) and the researcher perspectives gathered by close-ended questioning (e.g., through an instrument such as a survey selected by the researcher) ([Creswell and Creswell, 2018](#)).

The overall research design is illustrated in [Figure 3.2](#); as can be seen, this research is mostly qualitative. 'QUAL' stands for qualitative and 'QUAN' stands for quantitative as represented in [Figure 3.2](#). Capital letters indicate higher priority weight, and lower case letters indicate lower priority weight ([Cohen et al., 2017](#); [Creswell and Clark, 2017](#)). This research was initially intended to be conducted in two phases; however, the second phase was cancelled owing to a shortage of participants due to the COVID-19 epidemic and ongoing lockdown. The third phase was designed to focus heavily on QUAL as pandemic conditions precluded gathering a larger amount of QUAN data.

Figure 3.2

The overview of the research’s phases using mixed methods, influenced by Creswell and Creswell (2018) and Creswell and Clark’s (2017) convergent design




 No data collected due to COVID-19

Figure note: Capital letters indicates higher priority weight and lower case indicates lower priority weight.

Figure 3.3

The overview of research approach

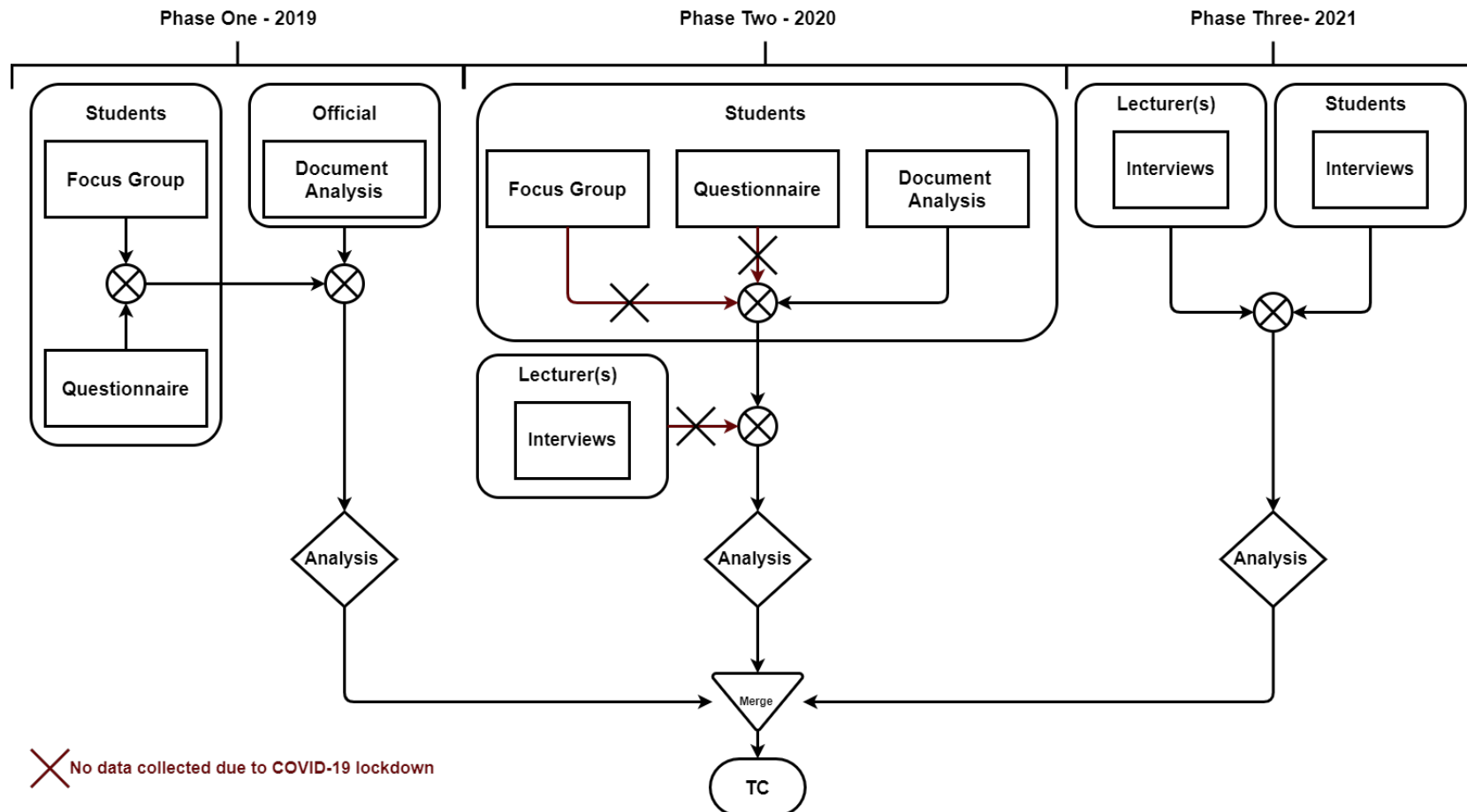


Figure note: Phase Two failed to achieve the intended results, thus Phase Three was created to make up for the previous phase's shortcomings.

3.6 Methods and Data Analysis

As seen in Figures 3.2 and 3.3, this study collected data using four methods: a questionnaire; interviews; focus groups; and secondary materials. The figure also shows which method was used during which stage of this study. The steps for data collection and analysis across the three phases of the study are described in detail in the sections that follow. Each method is described in this section along with the pertinent data analysis, which means that data analysis is integrated into the methods rather than treated separately.

Table 3.1 summarises the key aspects of the three Phases. Table 3.1 summarises the process and outlines each phase's specific steps, including data collection techniques, participant information, sampling, etc. The majority of the methods used in each phase are similar, so this section doesn't cover them individually by phase. However, the processes employed in each phase should be considered separately, as the needs of each may differ depending on the purpose of the study and its participants.

The planning and conduct of research were significantly altered by COVID-19. This section was created to demonstrate the research methods, and within this section, the steps for data analysis are described. As a result, the strategies used will be presented as a whole process rather than in stages. Despite the challenges posed by the pandemic, research was still able to be conducted and completed with successful results that could still be used to answer the research questions posed.

Table 3.1*Summary of research stages and methods used*

	Phase One	Phase Two	Phase Three
	Four semi-structured focus groups		
Data collection methods	Questionnaire	Document analysis	Five semi-structured interviews
	Document analysis		
Sampling	Convenience sampling	Purposive sampling	Convenience sampling
Sample technique process	Students who had studied sustainability papers and were interested in the study were invited	Students from two universities who had studied sustainability papers were invited but, due to the COVID-19 lockdown, response rates were low	Students who had studied sustainability papers and were interested in the study were invited along with a lecturer who had been introduced by all previous participants in Phase one
Participants	18 undergraduate students for focus group	5 undergraduate students	5 undergraduate students
	98 undergraduate students for the questionnaire		One senior academic
Discipline	Software engineering	First-year student with no discipline	Software engineering
	Electrical and electronics engineering		Chemical engineering
	Civil engineering		Fire engineering
	Material and processing engineering		Mechanical engineering
Gender	Mechanical engineering	unknown	Electrical and electronic engineering
	Male (12) and Female (6) for focus group		Male (2) and Female (3)
	No data for the questionnaire		
Data analysis	Thematic and descriptive analysis	Thematic and descriptive analysis	Thematic and descriptive analysis

3.6.1 Questionnaire

In social and educational research, questionnaires are commonly employed as data-gathering techniques (Cohen et al., 2017; Creswell and Creswell, 2018; Neuman, 2011). The questionnaire, as a useful and widely used tool for gathering data, provides ordered, primarily numerical, data that may be applied without the researcher's direct involvement and is generally simple to evaluate (Cohen et al., 2017). In addition, the questionnaire is primarily used to translate the research's goals and objectives into precise questions that can generate specific replies (Neuman, 2011). Because they utilise structured (closed or closed-ended) and semi-structured (open-ended) questions, questionnaires may collect both quantitative and qualitative data. Closed-ended questions require respondents to pick from a predetermined set of responses, whereas open-ended questions allow them to offer whatever response they choose (Cohen et al., 2017; Creswell, 2012; Gray, 2017; Neuman, 2011).

The major disadvantage of using open-ended questions to gather data is that they take longer for respondents to complete and for researchers to collate and analyse than closed-ended question forms. Closed questions are advantageous since they are quicker and easier to answer for both responders and researchers (Burton and Bartlett, 2009). In order to acquire as much information as possible from the respondents, a combination of open and closed-ended questionnaires was used in this study, with a particular emphasis on the closed-ended structure.

The purpose of the questionnaire was to find out how students feel about the course and sustainable engineering. There were 22 questions in total on the questionnaire, which was separated into two segments. Table 3.2 illustrates all the different sections' descriptions. Each segment contained three comparable questions about whether they should integrate their personal opinions with their professional opinions on the same issue, but in different fields. The majority of the questions were closed-ended, with the exception of a few open-ended questions on the course and sustainable engineering, in which respondents were free to express their opinions. Respondents also had the option of adding more information to closed-ended questions if they believed the offered response was insufficient. Because the time to gather data was limited, the supervisory team and two additional PhD candidates double-checked the questionnaire for clarity

and made necessary revisions. Furthermore, the participants for the questionnaire were chosen using convenience sampling.

Table 3.2*Sections of the questionnaire and their descriptions*

Key Concepts	Descriptions
Introduction	To inform participants of the study aim, description of TC and sustainability in the study context, and the study ethical considerations
Discipline information	To break down data based on discipline focus findings
Project and disciplines	To group respondents accordingly to the projects to provide different categories of data
Importance of sustainability in disciplines and personal perceptions	To rate the importance of sustainability in personal and discipline-based perceptions To determine discipline focus perceptions toward sustainability engineering To gather general information regarding how sustainability is viewed
Sustainability triple bottom line perceptions in disciplines and personal perceptions	To gather general information regarding how sustainability is viewed To help with FG questions and Phase two research design
Knowledge based questions	To test if respondents read the questions and test the questionnaire answers' trustworthiness
Course content list: Troublesomeness	Initial analysis of possible TC in sustainability according to different disciplines and in general
Personal and discipline based interest in sustainability	Obtaining additional information to cross-check with other questions To be able to use participants' perceptions and interest for answers provided to other questions

3.6.1.1 Sampling and Data Generation

Convenience sampling was used for the questionnaire since it was a very fast and straightforward approach to collecting data given the time restrictions I had in the first Phase. In addition, I was able to narrow down the pool of participants to include only those who best matched the study's demographics. Convenience sampling fits within the non-probability sampling approach, and matches the mixed methodologies, integrated qualitative design of this study (Cohen et al., 2017).

The most important motivation for convenience sampling was to acquire access to the most accessible participants (Gray, 2017). This research, as mentioned in section 3.2, leverages participants' perceptions and knowledge of the world they live in. As a result, only students with a firm grasp of what it means to be an engineer, as well as those who have completed the required courses on engineering sustainability, were allowed to participate. The participants recruited for the research were from levels 300 and 400 and were studying the sustainability engineering paper at the time of the invitation to the study. The students were asked to take part in the research after they had completed the paper so that they had learned what the paper had to offer. Students in years three and four of their studies would have adequate grasp of their disciplines and what they intended to achieve in the future. Respondents were from eight engineering disciplines: (1) Chemical Engineering (CHE); (2) Civil Engineering (CE); (3) Electrical and Electronic Engineering (EEE); (4) Mechatronics Engineering (MECHA); (5) Environmental Engineering (EE); (6) Materials and Processing Engineering (MPE); (7) Mechanical Engineering (ME); and (8) Software Engineering (SE).

3.6.1.2 Data Cleansing and Preparation

A total of 102 students out of a class of 200 responded to the survey. Three of the respondents' responses were later withdrawn since they were not engineering students and had no prior engineering expertise, lowering the number of participants for the statistical analysis to 99. Quantitative data from the closed questions was entered into Microsoft Excel and then transferred to SPSS for

additional analysis.¹ This process also included a review of the data for consistency, with the goal of removing any data that was inconsistent, such as responses including out of range or extreme numbers for some questions. The investigation, however, found no data that was out of range in the dataset.

3.6.1.3 Data Analysis

The questionnaire was created to elicit quantitative as well as qualitative data. Due to the fact that each dataset requires a unique analytic approach (Punch and Oancea, 2014), this study included both quantitative and qualitative data analysis techniques. The quantitative data from questionnaires were processed and analysed using SPSS 22 and Microsoft Excel, while the qualitative data from open-ended questions were analysed using computer-assisted qualitative data analysis software (NVivo11). However, the first analysis of qualitative data from the survey was undertaken with the use of Excel. The primary goal of utilising Excel was to generate visually appealing graphs that would aid in future data analysis and paint a clearer picture. The strategy for data analysis and the statistical methodologies used were determined by the nature of the research objectives, the methodology, and the features of the data.

Quantitative

The project was originally intended to employ two distinct sets of quantitative data over two periods. Due to the disruption of the study's second phase by COVID-19, only Phase One data could be analysed. The Phase One questionnaire was created to serve as the gateway to the Phase Two surveys. This research examined how students in various fields explain and interpret sustainability. Thus, descriptive statistics were preferred for quantitative data analysis, as they assisted in summarising data and providing a first insight into the engineering disciplines as a whole. In contrast, inferential statistics, which are based on the researcher's perspective, assist in identifying the perspectives and characteristics of participants. Inferential statistics is used to derive the researcher's primary conclusions and what he or she expects to learn about the collected data by analysing the means of various statistical tests, whereas descriptive

¹The questionnaire itself was on paper.

statistics is used to identify sample characteristics such as the overall sample size or demographic characteristics of the received data (Pallant, 2010). As a phenomenographic study, there were no preconceived notions about any engineering discipline's perspective on sustainability in engineering. As a result, no inferential statistical tests were required due to the nature of the research. On the other hand, descriptive statistics did give a concise description of the features of the many variables and statements in this study (Pallant, 2010).

Qualitative

Apart from the two open-ended questions, students were asked to provide general observations on the questionnaire and the course. Two more open-ended questions were included as a way for students to express their thoughts in the event that the offered response options were not practical. The responses to these questions were deemed to be the primary source of qualitative data for the questionnaire, with the others being eliminated. Due to the absence of a structure or framework prior to data analysis, as well as the absence of a pre-set theory in this study, an inductive technique was employed to analyse the data (Burnard et al., 2008). As a result, inductive thematic analysis was used to analyse the qualitative data obtained by open-ended questions throughout the questionnaire (Boyatzis, 1998; Burnard et al., 2008). To do this, qualitative data were classified, examined, and interpreted in connection to the study topics (Cohen et al., 2017; Punch and Oancea, 2014), and the research process was followed (Lacey and Luff, 2001). The replies of participants highlighted a variety of themes that shaped the research findings. The analysis of qualitative data in this study entailed evaluating, coding, and recoding all open-ended questions from surveys in order to uncover data trends and arrange the findings (Guest et al., 2012).

Excel was used to analyse the data for the questionnaire's open-ended questions. Each open-ended question had its own page, and the responses to each question were analysed independently. The responses of the participants ranged from a single word to numerous phrases. All sentences were analysed and classified according to the theme. The topic was determined either directly through the use of a keyword in the phrase, or through an analysis of the underlying meaning students were attempting to express. Despite the fact that NVivo was

utilised in previous parts of the study to generate a quantitative picture of the data, the questionnaire diagram was created using built-in calculations in the Excel file. Coding was used to identify emergent themes from participant replies. These topics served as the foundation for the second and third stages of the study, as well as the development of interview questions. Phase One data analysis was performed following the collection of Phase Two data.

3.6.2 Interview and Focus Group

The interview is a technique for gathering data through the use of questions (Johnson and Christensen, 2012) that is frequently used in social and educational research (Burton and Bartlett, 2009; Punch and Oancea, 2014) to elicit participants' perspectives on particular issues (Punch and Oancea, 2014). Interviews are beneficial for doing research that tries to comprehend people's lived experiences (Gray, 2017). There are numerous varieties of interview techniques, and the style used is determined by the inquiry's aims (Gray, 2017; Johnson and Christensen, 2012; Rowley, 2012). The interviewer may pose both open and closed questions to the participants (Creswell and Creswell, 2018; Punch and Oancea, 2014). Interviews can be structured, semi-structured, unstructured, or focus group interviews. In a structured interview, the researcher establishes the topics, concerns, and the questions in advance (Cohen et al., 2017; Punch and Oancea, 2014). In an unstructured interview, open-ended and thorough questions give participants with opportunity to make extensive responses (Punch and Oancea, 2014). A semi-structured interview combines features of the first two forms, allowing for planned topics but also allowing for detailed or alternative replies. However, in all interview styles, the researcher must guarantee that the interview questions accomplish the study objectives (Cohen et al., 2017).

The researcher used interviews in this study to learn more about the participants' experiences and attitudes (Punch and Oancea, 2014). As a result, semi-structured interviews were employed to allow participants to convey their perspectives and experiences with sustainability in their disciplines. The majority of interview questions centred on concerns raised during the preceding part of the investigation. Semi-structured interviews were undertaken to elicit information on participants' perceptions and experiences, particularly with regards to engineering sustainability. Since each discipline was examined separately, a diverse

variety of perspectives on sustainability within each discipline was collected. The interview's primary objective was to ascertain the presence of threshold concepts in various disciplines. Additionally, I gleaned additional facts by asking a variety of questions that were raised during the interview (questions available in Appendix 6.6 and 6.6).

The terms "focus groups" and "group interviews" are frequently used interchangeably to refer to a planned discussion (Punch and Oancea, 2014). Focus group discussion² is more appealing to higher education researchers and academicians than an individual interview because the data collection process extends the academic practice of exploratory discussion (Cousin, 2009). The primary goal of the focus group is to get people talking about the research questions. The group dynamic will increase the group's involvement and contribution to the topic. Everyone's experiences can be shared and compared in one location (Cohen et al., 2017; Cousin, 2009; Morgan, 1996). Morgan (1996) mentions sharing and comparing as a positive development process that allows the members of the focus group to clarify, extend, and review their knowledge. Focus groups with academics and students on sustainability, in particular, may aid in the definition of the TC. The researcher will serve as a moderator, which may benefit the group by making them feel more secure and in charge of the discussion (Cousin, 2009; Punch and Oancea, 2014). The ideal moderator for a focus group is someone who is comfortable interviewing in a variety of styles, from non-directive to directive (McQuarrie et al., 1991). The focus group is centred on the research questions, discussion topic, and participants. A typical focus group should have six to twelve participants and should last one to two hours (Cousin, 2009; Onwuegbuzie et al., 2009). The size is adjustable based on the participants' experience and knowledge (focused on a single topic) (Cohen et al., 2017; Onwuegbuzie et al., 2009). Over-recruiting participants is critical to ensuring their availability on a specific day (Cohen et al., 2017; Onwuegbuzie et al., 2009).

In this study, a combination of directive and non-directive approaches was used. The directive approach usually allows for excellent coverage of topics or more detailed coverage of specific topics of interest in the time available. Non-directive approaches provide more opportunity for group interaction and discovery and greater opportunity for the individual participants' views to emerge, rather than imposing the researcher's framing of the issues (McQuarrie et al., 1991).

²Used interchangeably with focus group.

3.6.2.1 Design and Development of Questions

This study used a phenomenographic technique, which collects data from a second-order perspective. That is why [Marton \(1986\)](#) favoured a semi-structured interview with a small number of participants. The data collection technique that followed this strategy was a “process of discovery, first focusing on each individual as a unique case” ([Ashworth and Lucas, 2006](#), p. 418). The interview questions focused on the students’ perceptions and experiences of the course, with a strong emphasis on engineering sustainability.

Bracketing is another critical feature of phenomenographic study. Bracketing entails classifying participants’ perspectives and assumptions independently of the researcher’s assumptions and interpretations ([Ashworth and Lucas, 2006](#)). This method was utilised to prevent researcher prejudices during participant interviews. As such, the researcher set aside preconceived notions, hypotheses, and prior study findings and concentrated only on the similarities and contrasts in participants’ perceptions and experiences ([Ashworth and Lucas, 2006](#)). The findings from Phase One aided in the process of bracketing. It should be highlighted that bracketing was used throughout this thesis, from the basic concept to the interviewing and data collection, data analysis, and reporting the findings.

Additionally, as is customary in phenomenographic research, interview questions were piloted prior to conducting interviews to identify any shortcomings and to hone the researcher’s interviewing abilities. Piloting interview questions entails determining whether they are appropriate for use in a real-world research situation by trying them on a small number of people. As [Bowden and Green \(2005, p. 19\)](#) noted, piloting interviews was critical for improving interview skills and “ensuring that the topic that interviewees are encouraged to discuss by the planned inputs is the focus of the research.”

Additionally, the pilot interviews were used to evaluate the interview questions in terms of their projected duration, as well as to try other interview techniques, such as determining whether interviews could be performed efficiently online. A PhD student was among the participants in the pilot interviews. Pilot interview data were omitted from the data sample. Additionally, piloting was utilised to evaluate the validity of the research methods in order to increase the dependability of the interview data ([Punch and Oancea, 2014](#)). As a result of piloting the interview questions, I was able to reword some of them when required. This

simplified and streamlined the interviewing procedure and the subsequent data processing phase.

3.6.2.2 Data Generation Process

Volunteer sampling was employed for interviews and focus groups, and participants were selected by requesting their participation (O'Leary, 2017). In order to do this, as part of the original invitation to fill out the questionnaire in Phase One, students were asked to indicate their interest in continuing to participate in the study. The date and place of the focus groups were predetermined, and participants were permitted to choose those that worked best for them. For Phase Three interviews, participants were also given predetermined dates and times that they could choose, with the venue announced later. Every interview and focus group was conducted in person and participants were informed that our discussion would center around their perception and experience with sustainability in engineering.

Volunteers were given access to an online information sheet and consent form prior to the interview. Participants were asked to confirm their agreement using an online Google form for their convenience. The information sheet gave a concise summary of the research's objective, methodology, and ethical issues. Participants were advised that their replies would be kept private and confidential. The information sheet also included an explanation of the study's implications.

To address ethical issues in this research, the respondents' comprehension of the information sheet was validated prior to the start of the interviews. In the introduction, the researcher invited participants to voice any questions or concerns about the research or their anonymity. None of the participants, however, asked for more clarification. The semi-structured interview inquired about the participants' perceptions of their discipline's interaction with sustainability, as well as their classroom learning experiences. Based on the participants' concerns and interests, their replies paved the way for more in-depth inquiries.

With the participants' consent, audio recordings were created and interviews were transcribed verbatim to prevent information loss (Punch and Oancea, 2014). Later, the interview transcripts were emailed to the participants so that they

could verify the accuracy of the information (Guba and Lincoln, 1994). The focus group transcripts were not emailed in order to protect the participants' statements from being used without their consent, as the number of participants was too large. Participants in this study are from various engineering disciplines including: (1) Electrical and Electronic Engineering (EEE); (2) Software Engineering (SE); (3) Civil Engineering (CE); (4) Mechanical Engineering (ME); and (5) Materials and Processing Engineering (MPE); (6) Chemical Engineering (CHE); and (7) Fire Engineering (FE).

3.6.2.3 Data Analysis

The themes that arose from the interview and focus group data were captured via inductive and deductive data analysis. The inductive analysis technique was used to engage with the data in order to establish categories and patterns (the relationship between codes, categories, patterns and themes) (Saldana, 2016). A deductive analysis approach was used based on characteristics of TCT (Meyer and Land, 2003). The themes were detected using Saldana's (2016) first and second cycle coding methods. Initial codes were developed utilising first cycle techniques (grammatical, elemental, emotional, and exploratory methodologies, as well as data themes) and were changed when new codes arose. Using the second cycle of coding - pattern and axial coding - the emergent codes were reorganised and re-analysed.

The themes found in Phases One and Three, with detailed explanation for each theme and sub-theme, can be found in Appendix 6.6. There are five main themes: Concept; Perception; Doubtfulness; Threshold Concept (TC); and Definition. The themes of Concept, Perception, and Doubtfulness were obtained using inductive analysis. The themes of TC and Definition were developed by deductive analysis. The theme of Concept encompasses all elements that contribute to a conceptual understanding of what something is or how particular aspects operate. The Concept should be recognised as a primary aspect of this study's findings since, under the theme of Concepts, participants provided several ideas that might aid in recognising threshold concepts in sustainable engineering.

The theme of perception focuses on participants' attitudes and behaviours toward engineering sustainability, although various elements of this theme touch

on a far larger range of topics, including education and politics. The participant perspective on these elements was critical in identifying the primary root cause problem that confronts engineering students studying sustainability. The codes that inspired the Doubtfulness theme were: Vagueness; Uncertainty; Misunderstanding; Leaving it to experts; and Alternate explanations for their coding intensity with respect to different disciplines. As the theme's name indicates, Doubtfulness refers to any instance in which students refer to a state of ambiguity and vagueness.

The TC and Definition themes were developed by deductive analysis. The TC theme refers to the primary qualities of TCT that were identified by participants. Similarly, the Definition theme encompasses participants' perceptions and definitions of sustainability in general and within their respective professions. For additional information, Appendix 6.6 includes a brief description of each theme and elements within it.

NVivo was used to code and generate relationships between participants' transcripts and their disciplines. Every single transcript was auto coded according to the participants' names and later categorised according to their disciplines. The data analysis relied heavily on NVivo, as the number of participants for qualitative data were too many, and therefore data analysis took a significant amount of time. Furthermore, this study's main purpose was to compare different engineering disciplines' perceptions of sustainability in engineering. Therefore, NVivo visualization helped to translate all qualitative data into graphs where I could more easily understand their meaning. These graphs can be found in Appendix 6.6, where each theme and sub theme is compared with all the disciplines participating in this study.

3.6.2.4 Participants' Information

The participants' demographic characteristics, such as employment history, geographical location, sexual orientation, and pseudonym, are shown in Table 3.3. Pseudonyms for participants are utilised throughout the findings and discussion to make the writing and reporting simpler to understand and to establish a more personal connection with the participants. When it comes to findings and discussion, participants' disciplines are crucial, and it's a good idea to be familiar

with their fields in order to understand their point of view. In terms of work experience, the majority of participants were full-time students, but for those who were employed, their opinion of sustainability and how the educational system may assist in addressing sustainability concerns was critical. That is why it was decided to categorise them so that their contribution could be more easily analysed during the discussion. Due to the fact that a small percentage of students were enrolled in a pathway programme that allowed them to graduate earlier than usual and did not require them to study the requisite courses for their degree, it was thought necessary to bring this out. The next sections identify the findings related to each of the five key themes described earlier.

Table 3.3*Focus group and Interview participant information - Phase One and Three*

N	Name	Sex	Discipline	Work experience	Local/International	Phase
1	Cody	M	Electronic and Electrical	Yes	Local	1
2	Hugo	M	Electronic and Electrical	Yes	Local	1
3	Sagar	M	Electronic and Electrical	No	Local	1
4	Dehirm Cilnal	M	Electronic and Electrical	Yes	Local	3
5	Akilah	F	Material and Processing	No	International	1
6	Aldwyn	M	Material and Processing	No	International	1
7	Huey	M	Material and Processing	No	International	1
8	Nyaja	F	Material and Processing	No	International	1
9	Ravyn	F	Material and Processing	No	International	1
10	Thaddeus	M	Material and Processing	No	Local	1
11	Aragon	M	Mechanical	No	Local	1
12	Lannis Krun	M	Mechanical	Yes	Local	3
13	Condan	M	Civil	No	International	1
14	Malchom	M	Civil	No	International	1
15	Aldona	F	Civil	No	Local	1
16	Gurinder	M	Software	No	Local	1
17	Meinrad	M	Software	No	Local	1
18	Osraed	M	Software	Yes	Local	1
19	Raynard	M	Software	No	Local	1
20	Tancred	M	Software	No	Local	1
21	Yell Davurson	M	Software	Yes	Local	3
22	Kairdra Of Daevon	F	Chemical	Yes	Local	3
23	Jenniye Orso	F	Fire Engineer	No	Local	3
24	Pyrrhus Epirus	M	Software	Professional (lecturer)	Local	3

3.6.3 Document Analysis

In research, secondary data refers to previously gathered information that was originally created for purposes other than the current research. Different types of secondary data exist, including numerical (quantitative) and non-numerical (qualitative) data (Gray, 2017; Johnson and Christensen, 2012). Secondary data, such as official documents, class reflections, and assignments, were used in this study.

All of the official documents used in this study are available online. I used university-supplied paper outlines that can be found using any search engine. As for the assignments in Phase One, because the students were working in groups, I couldn't view their work without the permission of each member of the group. Phase Two assignments, on the other hand, were completed independently, allowing me to analyse the records. As previously discussed, Phase Two data collection was severely disrupted by the COVID-19 pandemic, and therefore the number of participants was lower than expected.

Overall, the study relied on official documents and independent Phase Two assignments for analysis, while group work was not accessible without consent from all members. All relevant materials can be found online or through university resources.

3.6.3.1 Data Generation Process

Throughout all three phases of this study, all participants were asked for permission to analyse their assignments. As previously noted, in Phases One and Three assignments were completed as part of group work, and I required the permission of all team members to analyse their work. This proved to be challenging, and not all team members were eager to share their work. I was also not able to distinguish the individual work done on each assignment. Therefore, no assignments from Phases One and Three were analysed. However, since the majority of participants from Phase Two owned their work in its entirety, I was able to gather their university assignments and analyse their work.

3.6.3.2 Data Analysis

Similar to earlier steps, the documents were analysed using thematic analysis to identify themes within the data. As previously indicated, thematic analysis in this research included the organisation and description of the data. To this purpose, I sought to identify significant aspects of how participants presented their thoughts and experiences about LCA in the assignment. The inductive analysis technique was used to engage with the data in order to establish categories and patterns (the relationship between codes, categories, patterns and themes) (Saldana, 2016). A deductive analysis approach was used based on characteristics of TCT (Meyer and Land, 2003). Appendix 6.6 includes themes and sub-themes in Phase Two, which proved to be closely related to Phases One and Three. The closeness between Phase One and Phase Two findings was one of the reasons Phase Two data were kept after COVID-19 disruption.

3.6.3.3 Participant Information

The participants in Phase Two were from a different university. As I had no direct contact with the participants, and the documents were gathered with the assistance of Australian university administrators and professors, I do not have access to the participants' gender or background information, or know their real names. Furthermore, I knew they would not have chosen a discipline since they were all in their first year of study. All assignments and class reflections sent to me were assigned a pseudonym and are shown in Table 3.4. Throughout the results and discussion, pseudonyms for participants are used to make the writing and reporting easier to grasp and to develop a more personal connection with the participants.

Table 3.4

Participant information for document analysis - Phase Two

N	Name	Discipline	Local/International	Phase
1	Corwin	Unknown (first year student)	International/Australia	2
2	Ervin	Unknown (first year student)	International/Australia	2
3	Joyab	Unknown (first year student)	International/Australia	2
4	Pin	Unknown (first year student)	International/Australia	2
5	Treowe	Unknown (first year student)	International/Australia	2

3.7 Trustworthiness

Research credibility relates to research quality, which is widely defined in respect to numerous research paradigms and methods (Cohen et al., 2017; Shenton, 2004). The significance of qualitative research is contingent on its dependability, which includes credibility, transferability, dependability, and confirmation (Shenton, 2004). Guba (1981) saw these four trustworthiness elements as an alternative to validity and reliability in quantitative research. Credibility is synonymous with internal validity, transferability with external validity, dependability with reliability, and confirmability with objectivity. To strengthen the credibility of this research and confidence in its results, a mixed method approach incorporating several data collecting tools and data processing techniques was used to enable triangulation (Shenton, 2004).

The quantitative parts of the questionnaire were submitted to tests for validity and dependability through content validation. When applicable, triangulation, member (participant) checks, and peer debriefing were applied to qualitative data to enhance the quality of the study. Also, a phenomenological technique, bracketing, was used to eliminate bias induced by the researcher's motivations or interests in order to strengthen the confirmability of the study (Lincoln and Guba, 1985). Prior to conducting interviews, interview questions were tested wherever possible, and statistics were reported in full.

Triangulation

Triangulation is a suggested method for acquiring a more complete and comprehensive knowledge of the topic being investigated. Triangulation necessitated the use of a variety of methods at various stages of investigation, from original conceptualization and theory application, through data collection and analysis, as well as utilizing both qualitative and quantitative data collecting techniques, such as questionnaires and interviews (Lincoln and Guba, 1985). I employed a mixed methods strategy to gather data in order to accomplish triangulation, which included a questionnaire, focus groups, interviews, and documentation analysis.

According to [Shenton \(2004\)](#), several data sources and informants might enhance triangulation. To meet these requirements, the questionnaire was designed to capture a wide range of data from participants. In addition to discipline-specific questions, the questionnaire also had some generic questions designed to reduce the participants' anxiety about answering the questions. Initially, this research intended to interview first-year individuals in order to compare their perspectives with those of fourth- and third-year participants in Phase One. However, COVID-19 prevented me from doing the investigation. To address the challenge, I set out to conduct Phase Three interviews with participants from two independent cohorts. A portion of the participants were from the new cohort, while the remainder were from the cohort from the prior year.

Peer Debriefing

Peer debriefing establishes the validity of the results by minimising bias in qualitative research, hence bolstering the data's credibility ([Lincoln and Guba, 1985](#)). This study was overseen by two professionals from its inception to its conclusion in order to ensure its trustworthiness. My two supervisors are well-versed in qualitative and quantitative research methodologies. One is an expert in educational research, while the other is an expert in engineering research; my third supervisor was not part of the team for the initial stages of data collection but she was expert in both fields and helped with ensuring the trustworthiness of this study. Debriefings were conducted through continuing supervisory meetings and frequent contact with my superiors.

Member (Participant) Checks

In order to satisfy the need for credibility in this study, the transcripts of interviews were distributed to the participants. To this aim, the participants were provided the interview transcripts for verification. A transcript of an interview with each participant was sent to them so that they could verify the correctness of their record. They were requested to add to, remove from, or comment on the material as I planned to use interview data as direct quotations. Additionally, participants were asked to affirm that the transcript matches their statements and accurately expressed their meaning. Since audio recordings were created of

the interviews, participants in the study validated the accuracy of the recordings and transcripts ([Shenton, 2004](#)).

There was no member checking for focus groups since there were too many participants in each group, and it was difficult to tell who in the group said what once the audio recording was transcribed. The participants were advised beforehand that they would not be allowed to change their comments, and they were given the option to leave or remain silent if they felt uneasy.

Transferability

Transferability may be demonstrated in qualitative research by giving evidence from the findings. According to [Lincoln and Guba \(1985\)](#), it is the obligation of the reader to determine whether or not a study is applicable and instructional for their own research. The researcher, on the other hand, is responsible for “offering the database that enables future applicants to evaluate transferability” ([Lincoln and Guba, 1985](#), p. 136).

Following the advice of [Lincoln and Guba \(1985\)](#), I have collected “rich descriptive data” and offered a thorough account of the study procedure. Specifically, a comprehensive and complete description of the data collection processes and techniques has been provided. This provides a clear image of the study environment, which helps readers determine if the findings may be applied elsewhere.

Dependability

The capacity to replicate research is implicated by the attribute of dependability. According to [Lincoln and Guba \(1985\)](#), dependability in research is achieved by the use of correct and consistent data. Dependability and data stability could help researchers to reproduce previous findings at various dates and in varying settings. Following the advice of [Lincoln and Guba \(1985\)](#), an audit trail and a record of every step of the research process was established.

I used a password protected Google drive to compile, organise, and archive data including questionnaires, interview recordings and transcripts, and supplementary materials like consent forms. Therefore, I had access to data anywhere and anytime to review when necessary.

Each step of the research procedure was documented in detail, from participant selection and data collection through analysis and interpretation, providing a thorough account of the processes involved in doing the research and reporting the results. Because of this, the study provides data for other researchers to replicate the study under other conditions ([Lincoln and Guba, 1985](#); [Schwandt, 1994](#)).

Confirmability

To demonstrate confirmability in qualitative research, the researcher must give a basis for the reader to trust that the study results are based on the participants' perspectives, as opposed to the researcher's own interests, opinions, preferences, and judgments. For the purpose of establishing the research's confirmability, triangulation was employed to limit the influence of researcher bias. I also explain the rationale behind my research-related choices. This study used techniques such as an audit trail to document the choices made and actions done ([Shenton, 2004](#)). In addition, phenomenography was used to mitigate the influence of my personal predispositions. As part of this methodology, bracketing tactics were used at several phases of the research, from data collection through report writing ([Lincoln and Guba, 1985](#)). Before conducting interviews, interview questions were tested, and data was provided in detail.

3.8 Ethical Considerations

Ethical concerns in this study included preventing emotional and physical damage to participants, obtaining informed permission, preserving participants' privacy throughout the research procedure, and resolving problems of data confidentiality ([Berg and Lune, 2017](#)). Such principles underpin the ethical aspects in educational and social science research ([Cohen et al., 2017](#); [Creswell and Clark, 2017](#)). Ethical considerations were examined at every stage of the investigation, and the University of Waikato Human Research Ethics Committee provided ethical approvals with rules and guidelines to be followed at every stage of the research (Appendix 6.6 for Phase One and Appendix 6.6 for Phases Two and Three).

3.8.1 Avoiding Harm to Participants

In this study, the risk of harm was negligible. However, it was possible that participants could feel embarrassed by answers provided in front of their friends or concerned that the recorded audio may be used against them. To decrease this concern, the participants were informed on the consent form that they had the right to refuse to answer any of the questions, and that they might withdraw from the research at any time before the analysis began. For instance, it was indicated that a participant may withdraw from the survey by not submitting it, request that their interview data be removed, or ask that their assignments not to be analysed. In addition, participants were notified before interview and focus group sessions that the sessions would be recorded and transcribed. They were assured that any harmful data that could be traced back to them would be removed.

It was also accepted that participants were spending their time, therefore I made sure to restrict the questionnaire to 20 minutes, interviews to 60 minutes, and focus groups to 45 minutes, which I communicated to participants. Cultural and societal concerns were also taken into account, and I consulted my supervisors at every stage of the study. Due to the fact that my cultural background varied from that of the participants, I also considered potential cultural sensitivity difficulties in my study. In this respect, a Māori mentor and my supervisors aided me.

3.8.2 Informed Consent

By use of an information sheet, the participants were made aware of the research's ethical considerations, including privacy, confidentiality, and withdrawal rights ([Johnson and Christensen, 2012](#)).

The sheet included information and directions for all aspects of the study, including the nature of the research, how the results would be used, and how I would preserve their privacy and use their data solely for this study. Before agreeing to be a volunteer participant in this study, participants were informed of their rights in the research process and procedures; their voluntary contribution to the research; potential threats and benefits; and ethical concerns ([Cohen et al., 2017](#)).

3.8.3 Privacy and Confidentiality

The primary issue for ensuring confidentiality in this study was that the research data would not betray the respondent's identity ([Johnson and Christensen, 2012](#)). Consequently, data are often given in aggregate form. In Phase One, participation in the survey was anonymous, and I have utilised participant numbers and pseudonyms when referencing them and quoting them directly. Phases Two and Three interview and document analysis data are provided under pseudonyms, and all traces of respondents' identities have been deleted. After participants had verified and approved their interview transcripts, only then were direct quotations from interviews utilised. It is acknowledged, however, that anonymity and confidentiality cannot be guaranteed in research ([Cohen et al., 2017](#)), particularly for a tiny nation like New Zealand. Therefore, all participants were advised of the potential dangers, and gave their agreement to participate in the research.

3.9 Chapter Summary

The philosophical view informing this research is that humans construct multiple realities in relation to different aspects of the world. Therefore, questioning engineering students' perceptions and experiences regarding sustainability and threshold concepts in their disciplines helped me find the multiple realities of sustainability in engineering education.

This chapter provided an overview of the research methodology and methods that were applied over the course of this research investigation. The epistemology, ontology, and theoretical perspectives were discussed, in conjunction with the methodology and methods, and their justifications and explanations were provided. This chapter provided further insight into the data collection process as well as the selection of study participants. The last sections discussed the reliability of the study and detailed the steps taken to resolve any ethical concerns raised.

The following chapter presents the findings, organised according to the overall study's key themes rather than the methods used. In this way, it can be seen that the results of the study are most effectively and meaningfully presented through the investigation of these key themes.

Chapter 4

Findings

4.1 Chapter Overview

This chapter describes the findings of this research. This study was conducted in three phases, as previously stated. Appendix 6.6 contains the detailed data analysis, including themes and subthemes. This chapter, however, is not organised by phase or theme. Instead, the findings chapter has been divided into two sections: qualitative and quantitative.

Figure 4.1 depicts each category, along with the phases and headlines used in each section. The multiple phases of this study were combined into a single, comprehensive document due to the similarities between phases and my decision to use the collective experiences of diverse engineering disciplines. The perspectives of all participants were considered collectively rather than individually. A unified analysis of the collective experience could be achieved by compiling all findings from the qualitative and quantitative sections of this research.

The perspectives of all participants were considered collectively rather than individually. This collective mindset was used to develop a shared understanding of the engineering experience, which accounts for the research's diversity of voices. Each heading has been carefully selected for a relevant connection to all phases.

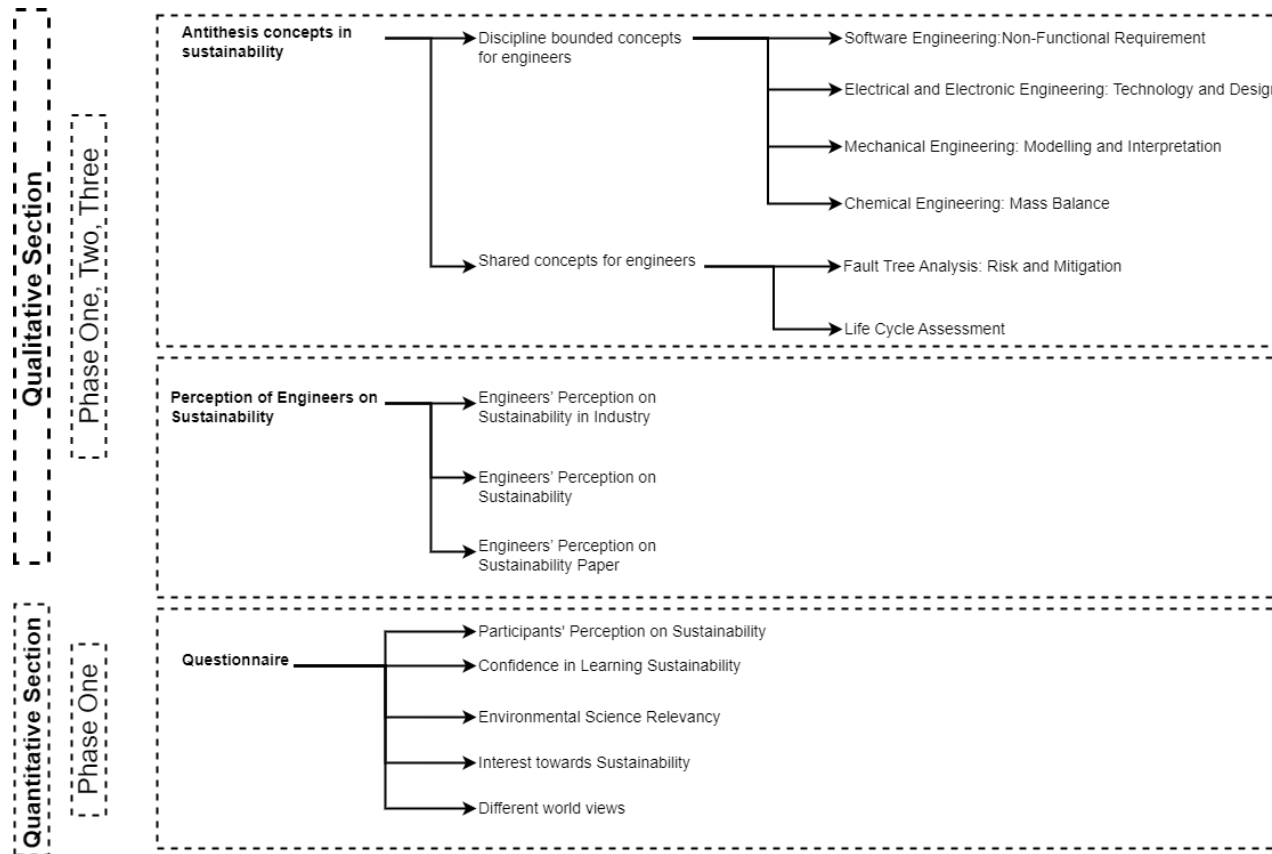
The goal of Phase One was to provide background information for the second phase and to assist with in-depth quantitative data analysis. Phase Two was

cancelled due to a lack of participants as a result of COVID-19. Later, Phase Three was created to help mitigate the lack of data. Please keep in mind that, despite the fact that the chapter has been divided into three main sections, understanding the interpretation is impossible if any section is skipped. The true interpretation of what the participants were communicating can only be understood with a holistic approach to the findings.

Given the constraints I faced, I did my best to provide robust data. It is important to note, however, that this data was obtained using common scientific assumptions and unique statistical techniques, and it does not accurately represent the facts.

Figure 4.1

A summary of findings chapter sections and subsections



4.2 Antithesis Concepts in Sustainability

This section discusses a collection of concepts/ideas¹ presented by participants that are connected to competencies required in sustainable engineering education. This section contains numerous components crucial to either generic or discipline-specific engineering education. The first half of this section, [Discipline Bounded](#), deals with concepts that are exclusive to one or two disciplines. Following this, Section [4.2.2](#) presents a collection of broad ideas that have been found to be relevant in more than two disciplines. The connection that participants identified between sustainability and their discipline is one of the significant discoveries in this study.

This section is titled “antithesis” because I wanted to highlight the stark contrast between concepts taught to students and what students believe is important. This contrast between ideas in sustainability education and what I discovered in this study allowed me to conclude that there are significant similarities between what sustainability education should be in engineering and what students are already learning. Students in engineering do not feel, however, that they have a bond with the subject, and this is focused on in depth in the discussion. This section is the primary reason for developing the back-room liminal model.

4.2.1 Discipline Bounded Concepts for Engineers

Discipline-bounded concepts are a significant finding that emerged from the data. It is best characterised as a collection of concepts that are distinct to one or two disciplines. The findings in this section illustrate that participants preferred to be taught about sustainability utilising concepts that are directly related to their disciplines. Additional data analysis revealed that there are essential concepts that are individually tailored to certain disciplines. For example, the data shows that [Materials and Processing Engineering \(MPE\)](#) and [Civil Engineering \(CE\)](#) were the only disciplines to discuss “Recycling” and “Pollution”. For [Software Engineering \(SE\)](#), “Algorithms” is the primary concept mentioned throughout the transcripts. [Electrical and Electronic Engineering \(EEE\)](#) were more interested in “Automation”, and “Designing”. “Modelling and visualisation” are reserved for [Mechanical Engineering \(ME\)](#) and [Fire Engineering \(FE\)](#)

¹Idea and concept will be used interchangeably.

participants. Finally, [Chemical Engineering \(CHE\)](#) suggested "Mass balance" as bounded concept.

The conflict between different engineering disciplines and how they conceptualise sustainability has been demonstrated in this section to some extent and will be highlighted further in the upcoming sections as we delve deeper into participants' [perspectives on sustainability](#). These findings demonstrate that each discipline has its own definition of sustainability, and that what one discipline holds to be true may not be true for another. This section distinguishes disciplines from one another so that it is easier to understand participants' points of view without being clouded by other disciplines.

Software Engineering: Non-Functional Requirement

The category [Non-functional Requirement \(NFR\)](#) is unique in that it has two subsections (i.e. algorithms and information technology security²), that are specific and interlinked to [SE](#) only. Pyrrhus considered [NFR](#) to be a major concept for [SE](#), even announcing it to be threshold concept in sustainability for [SE](#), as indicated in the paragraph below. Pyrrhus was not initially aware of this and it happened to be a moment of transformation for him as well.

...you know, **maybe the threshold concept is what we discovered just now because you helped me highlight what is the sustainability component into this.** And this is something that, perhaps, myself hadn't clearly understood, because I'm not clearly communicating it because I have it somewhere in the back of my head, but I'm not clearly saying it. I think this is a result of this discussion as well... So you know, maybe the threshold concept is that sustainability is another non-functional requirement for software engineering... And as such, this adds certain design and operational constraints for software, like software needs to be designed in a specific way; it needs to operate in a specific way such that it is sustainable. And from a technical perspective, that might mean a number of existing things that we rarely discuss. So we're discussing about over-provisioning, like no provision to many machines. But why? Well, because we're trying to be sustainable. It's

²It is also known as cybersecurity.

not only because we're trying to make money, right? Even though sometimes this is the primary motivation, so in many ways, making money seems to be the sustainable way. Because usually money connects more energy burnt. So maybe there's a connection here... (SE, Pyrrhus, Phase 3, 2021).

The concept of sustainability, as Pyrrhus discusses, has been present in SE; however, the focus has been misplaced. The concepts and issues were framed in a way that suggested that the major purpose was to save money for the firm and clearly generate more money. However, as Pyrrhus noted, if all the issues are to be provided with an example as to why it is essential, then the argument might be switched to sustainability instead of presenting an economical standpoint. If sustainability is to be taught as a NFR of software engineering, then possibly that could aid students with their comprehension. Pyrrhus provides the following explanation:

maybe that's it, like highlighting sustainability as a non-functional requirement of software systems. And then looking at all the implications that this has, during its design. And during its operation... (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus emphasised how it is vital to monitor our activity in terms of energy, material, and CO₂. As he stated in the following excerpt, by engaging students with how every stage of their design, testing, and maintenance requires a certain amount of energy, then possibly they will be able to adjust their mindset to operate more effectively and in a manner still be able to be cost-effective for the company:

...So if we're talking about sustainability, we have to somehow connect with emissions, I guess, or with energy requirements. So software doesn't run for free. The software requires energy to run. The software requires computers to run on, which require energy and materials to run on. And software needs to be designed by people who have their own processes. And they also burn energy and use resources while they're making the software. Yeah. So maybe, maybe this is something that we need to more explicitly communicate to students that every time that you're doing anything, this causes a certain, you know, a gram of CO₂ to be emitted. Like, what

are the repercussions of each and every action, even bad management of software projects, because you redo the same thing. And again, and again, and again, like this is, this is why we're insisting about code re-usability, because you don't want to be making from scratch, not only because it's, you're not going to be able to make that much money because you sell the same thing again, and again. And again, because you're wasting resources. (SE, Pyrrhus, Phase 3, 2021).

SE participants will expand on what Pyrrhus discussed about NFR in the following subsections. As Pyrrhus implied, algorithms and efficiency are part of NFR. The importance of NFR is that it is easily missed and ignored as it is one of the main discipline bounded concepts in SE.

Algorithm and Efficiency

Algorithms were one of the notions exclusive to software engineers. Although algorithms may be classed under design and energy, they appear to be too specific to be placed under any other categories. For example, an SE respondent to the questionnaire explained, "when automating a job involves consuming a resource, precautions must be made to decrease the use of these resources. This implies sensors must be reliable, data computations and interpretation must be exact" (ST4, software, QUS, 2019). This passage shows clearly the relevance of algorithm and efficiency. Furthermore, Raynard stated that when it comes to software engineering, algorithms should be the main focus of a sustainability paper:

... let's say you just have software engineers. They make a product like a website or Photoshop or something. It does not really have an environmental impact per se, other than running on a computer that has environmental impacts. I think having a software engineer who is part of another project that is actually on the physical side and can make that more efficient and can make it more environment friendly... if you are designing an automated plant that makes, I don't know, develops steel or something and you have got the program that is running all these robots, doing all these kind of

stuff, that is going to the way you do the calculation and stuff will definitely going to have an impact... (SE, Raynard, Phase 1, 2019).

Raynard and other SE participants further emphasised the importance of algorithms by illustrating this through a [Life Cycle Assessment \(LCA\)](#) assignment where they examine traffic lights' on/off time at intersections. Raynard discussed how they chose to implement a more efficient traffic signal control system in order to save time while also improving the environmental outcomes (i.e. they devised a new algorithm that allows for more precise traffic light regulation than is currently in place).

... we were talking about traffic lights, which we did the project on, if you have like different algorithms for how the traffic lights go green and red ... if someone waiting at the traffic lights for longer, that uses more fuel ... less about actually implementing traffic system but the software running on the traffic system ... (SE, Raynard, Phase 1, 2019).

Raynard went on to say that efficiency in his field is more about clever design and consuming less RAM. Raynard perceives his discipline and what is deemed efficient significantly differently, as seen here. He uses an automotive vehicle as an example to demonstrate what it means for a mechanical engineer to be efficient:

When you talk about efficiency in other disciplines, for example, you are building a car as a mechanical engineer, your efficiency is how much fuel usage you're getting per mile or whatever but when you say can you analyse this program and its efficiency, you are going to talk about memory usage, and clarity of code and all of this stuff is not really relevant to the environment in any such way. So, it is kind of hard because none of our previous papers talked about carbon emission and not so much electricity usage either (SE, Raynard, Phase 1, 2019).

Yell's perspective on algorithms was in some way tied to energy consumption. Yell mentioned, "I guess that's one way of being sustainable in terms of software; you have to be able to deal with the cost of using that computing power and the effects of how much energy is used." He further explained, "the benefit of your software, as you know, sits in the negative effects of the electricity we can

use.” Yell’s argument for why energy and power usage are important to software engineers begins in the following excerpts, as he points out that a lot of intensive computation occurs currently through the use of AI and cryptocurrency. He believed that students of software engineering should be made aware of the amount of energy consumed by every computational task, as he believed that this is one of the factors that is overlooked when it comes to educating students about sustainability in his discipline. In this way, he confirms that algorithms are a critical component of software sustainability.

Because right now in software...there’s a lot of computation done for things like machine learning and AI. There’s heaps and heaps of computational power that’s required for that sort of stuff. I mean, when I’ve been talking about cryptocurrencies, it’s the amount of mining, like the amount of energy that it takes. Yeah, and just making the software engineers aware that using or doing more computation takes more energy and how energy use impacts the environment (SE, Yell Davurson, Phase 3, 2021).

Yell continues by describing how he was not taught in the paper about higher levels of thinking about sustainability, either in his disciplines or on the project he was working on. He was intrigued by energy efficiency and improved algorithms that focused on system control at a higher level. He felt that reducing energy waste in processing power would make the system more sustainable. He said he had to research how to make a sustainable product using renewable resource materials with his hardware, producing an autonomous harvesting machine.

And that sort of cutting down is done at a very high level...So that’s something that requires a lot of expertise to be able to recognize that this is using too much computing power. We can cut it down and stuff like that. Yeah, so that wasn’t stuff that wasn’t really taught in the paper (SE, Yell Davurson, Phase 3, 2021).

Additionally, discussions on energy and algorithms inevitably lead to data centres. Yell hinted toward data centres, and he expressed an interest in using them as a case study for software engineering students conducting LCA. The paper’s major component was an LCA report, and students were asked to use real-world case studies to conduct a thorough examination of their chosen items. Yell addressed how critical load control and balancing are to the operation of any

data centre. Yell along with other SE participant all mentioned Pyrrhus where he taught them how to be sustainable.³ Yell's excitement for data centres and how they should be handled was evident in the following excerpt:

... but even coding in the data centres? Yeah, in terms of load management, load balancing, stuff like that is used. But then you're getting too far. And I feel like that software, and it's not an environment. Yeah, so I think [redacted] teaches stuff like that. It's stuff like how the work is distributed among the different computers. Oh, yeah, that's awesome. I think that's what it looked like (SE, Yell Davurson, Phase 3, 2021).

The following excerpt goes into depth on how a well-designed algorithm can help with sustainability. "Relaxing requirements" is a concept used to describe the line between sustainability and sophisticated software design. The easiest approach to express relaxing requirements is that, when machines are not required to be active, they are placed in the idle stand. Pyrrhus mentioned the Google search engine as an example that might be fascinating to adopt. Relaxing requirements might be activated by user request and, in a way, would prolong your search in order to conserve energy.

Like a very common solution, or approach to this problem is what we call to as relaxing the requirement and relaxing the requirement means that do you really, really, really need when you search on Google to get your response? In always in sub-second speeds? Like, would you be okay to have a green search for Google? That you click it, and sometimes you get your response within under a second, but sometimes it takes 10 seconds? Like, would you be okay with something like that? Maybe some people would be okay and say, look, you're doing a green search? Why, if I have this as a software engineer, I can do advanced scheduling. And I can say, look, I'm going to try to place your request in one of the existing machines because and I will wait a bit until they become free to put your request is going to be a bit of a delay. The alternative is, I will have to have a machine on all the time so that you can be served, like, so what is the likelihood, right, that you will be served other lower speeding, and it's okay if you are? Yeah. So these are all of

³Pyrrhus was mentioned in all phases and he was interviewed for this study.

these are techniques that they should be thinking in such a paper, and each of the disciplines, so, I can go way more in-depth now in software and computer Engineering, but you should essentially give them these hints and let them loose. Like, what is the effect of machine learning training? Again, what is the effect of testing? What is the effect of parallelism, all of these things, and then this is something that is software (SE, Pyrrhus, Phase 3, 2021).

Many of the concepts highlighted in this section, such as algorithms and efficiency, are unique to the field of SE, as expressed by the participants in this study. The SE participants' connection to sustainability elevates what Pyrrhus indicated by presenting NFR as a threshold concept. If you go further into the ideas behind efficiency and algorithm design, you will find that the main motivation for participation is to cut down on energy waste and enhance the systems. Therefore, there is a hidden, or more accurately, NFR for SE.

Information Technology Security

Another discipline-bounded concept that was only brought up by SE participants was cybersecurity (Information Technology Security).⁴ The discovery of cybersecurity was associated with SE participants' doubt about providing alternative justifications for why sustainability should be prioritised in their field. For example, the CE participant questioned whether cybersecurity and sustainability were compatible in software engineering during one such debate. While SE participants agreed that cybersecurity is akin to sustainability, the participant from CE did not see their point, believing cybersecurity does not have any connection to sustainability.

Cybersecurity was relevant! It was something that we were more obviously interested in than a building; that is why we did not do civil engineering; I guess that is why we think it was useful (SE, Raynard, Phase 1, 2019).

Tancred followed up on this assertion by emphasising the importance of cybersecurity and risk management to the sustainability of SE:

⁴The protection of computer systems and networks against information disclosure, theft, or damage to their hardware, software, or electronic data, as well as interruption or misdirection of the services.

When it comes to software sustainability, cybersecurity is resilience, and the risk is an attack (SE, Tancred, Phase 5, 2019).

Yeah, we could relate it back to sustainability (SE, Raynard, Phase 1, 2019).

Although the CE student understood the SE perspective on cybersecurity and its relationship to sustainability, having spent an entire semester as a member of their group, she was not convinced that this was the only way to ensure software sustainability. Another exciting moment from the focus group was when Osread could clearly interlink the cybersecurity concept and sustainability to the SE discipline. He explains how cybersecurity can have an effect on energy and security: the optimal and efficient system design, which only SE would understand, as he puts it. It seems the sustainability they were taught was primarily focused on the environment, and SE participants were looking to find their connection to the environment rather than being told the facts.

It was related to software sustainability! But not environmental sustainability (SE, Raynard, Phase 1, 2019).

I can see how you could make it relevant to software sustainability as in for the environment, but it still going to come down to energy usage, so they were talking about card access and doors and so the way you program, the delay time till the door opens, the traffic, or maybe the sensor that act like a power mode that reactivate by itself and then it comes on. That and the energy where it's kind of, if you use renewable fuels, that sort of thing... (SE, Osraed, Phase 1, 2019).

Well, I agree with Osraed, that I can see how sustainability can relate back to cybersecurity but it did not make any sense to me (CE, Aldona, Phase 1, 2019).

Yeah, but he was talking about the sustainability of the software. And there is environmental sustainability, and they are a totally different thing (SE, Tancred, Phase 1, 2019).

Raynard defined cybersecurity for SE by emphasising the disparity between disciplines' perspectives and what they are taught to perform. According to Raynard, software and cybersecurity are inextricably linked, since cybersecurity is

one of the most important components of his discipline, just as it is for CE in terms of preventing a building from collapsing, as seen below.

The sustainable building is one that does not have walls falling over and roof caving in. However, a sustainable program is one that you don't have to keep patching. I guess leaks of data and of vulnerability for attackers and stuff. So, if you release a cybersecurity application or something, you don't have to go back and keep fixing bugs, that kind of.... And you can move onto the next project. That is the finished project; it is like a cybersecurity project is like a finished building (SE, Raynard, Phase 1, 2019).

Additionally, Yell emphasised how cybersecurity is the technical expertise necessary to enhance sustainability in SE. Yell's perspective on sustainability and how it pertains to software engineering leads him to discuss nuclear power facilities and their accompanying security measures. As seen in the next paragraph, Yell is discussing the nuclear plant's cybersecurity and how it is one of the most technical aspects of SE: "sustainability is not a broad concept for SE", Yell noted. Rather, it is intimately linked with systems and the protocols by which we interact with those systems, "whether biological or technical."

...when we talk about increasing sustainability, it's like, "How do you increase it?" Then it gets a bit too technical. Like, what systems do you put in? Because if I talk about what systems to make for my nuclear plant to make it secure, then it's really deep in terms of software (SE, Yell Davurson, Phase 3, 2021).

Yell was not alone in his assessment of the significance of cybersecurity to software engineering. A respondent from the questionnaire who was not from the software engineering field also emphasised the significance. It was said that, if it weren't for security, there may be a negative impact on the environment. Yell pointed out, for example, how nuclear reactors are shielded from assault, which benefits the environment by not risking attacks.

I learned how important cybersecurity is to sustainability and what impacts it can have on the environment if there wasn't any cybersecurity (ST2, Civil, QUS, 2019).

The significance of cybersecurity and its role in software engineering was discussed further, but as indicated below, the implications were emphasised, and it was underlined that, not only the environment, but individuals, might be protected from an assault.

We learnt that the main sustainability problem in cybersecurity is if there's an attack, it can harm the environment or people (ST5, Software, QUS, 2019).

As mentioned in the following excerpt, Pyrrhus emphasises cybersecurity as one of the primary concepts within the software engineering discipline. Therefore, as a leading expert in software engineering, he confirms what everyone else has been trying to say. His assessment of how important cybersecurity is, and how it is part of the [NFR](#), demonstrates the boundedness of cybersecurity to [SE](#).

Cybersecurity, it is another non-functional requirement, right? So our systems need to be secure. And you're going to find a very large intersection. Now, what's going to happen if your systems are not secure? Like, if we think about that, you will end up in a situation where you will waste a ton of design time and computing time of your people trying to patch up things. It was going to bring your whole system down, like the hospital,⁵ like what if that, and then you look at the domain ([SE](#), [Pyrrhus, Phase 3, 2021](#)).

As the name implies, and as this section demonstrates, cybersecurity is the process of defending systems, networks, and programmes against digital threats. According to [SE](#) participants, the significance of cybersecurity lies in the boundedness of it and how it is directly tied to [SE](#), although mostly neglected when it comes to sustainability education.

⁵In mid-May 2021 hospital computer systems and phone lines run by the Waikato District Health Board (DHB) in New Zealand were affected by a ransomware attack. On 25 May, an unidentified group claimed responsibility for the hack and issued an ultimatum to the Waikato DHB, having obtained sensitive data about patients, staff and finances. The Waikato DHB and New Zealand Government ruled out paying the ransom.

Electrical and Electronic Engineering: Technology and Design

The study findings have shown that technology and design are intertwined; i.e. superior technology facilitates superior design, and vice versa. Design and technology were overemphasised among [EEE](#) participants. It seems that a guest speaker introduced the participants to the notion of technology as a panacea for engineering sustainability. Hugo recounted how a guest speaker introduced the concept of technology, and Cody soon corroborated his assertion by comparing the design requirements for an old and new dishwasher.

... sustainability is actually related to technology, so the better technology you have, the more sustainable you will become ([EEE, Hugo, Phase 1, 2019](#)).

... technology makes it easier...using the dishwasher as an example. You can design a soap that uses less water, and the dishwasher will use less water as well, so you can just toss everything in there and use less electricity, less water, and fewer chemicals ([EEE, Cody, Phase 1, 2019](#)).

Hugo, Cody, and Sagar went on to explore and imply that technology and good design may be related to [EEE](#) in terms of sustainability. Since, as technology has advanced, many devices and components have become too tiny to be fixed by consumers. As a result, Cody said that there is no means for consumers to fix their devices; therefore the landfills are filled with E-waste that can't be recycled or repaired. He proposed a better design so that consumers would be able to repair electronic devices in order to be sustainable:

... Basically, no one wants to fix anything, ... they will just buy a new one. So now we have landfills filling up with E-waste. So, I think the consumer needs to be a target as well. Or maybe it needs to be easier to fix ([EEE, Cody, Phase 1, 2019](#)).

In light of Hugo's previous work experience in the industry, he contradicted Cody's remark and argued that there is no way to fix anything because everything has become compact in recent years. He went on to say that they should instead put more effort into design. Hugo and Cody's conversation, summarised below, demonstrates the significance of good design, particularly in [EEE](#).

... we are at the point that we are not able to repair... since everything is getting smaller and compact... so you will throw it out when it does not work. Sure, maybe we can design electronics a little bit more resilient to ESD and something like that, and I think that is where, if I was giving a little direction for where the EEE side of sustainable engineering could be taught, here is literally some practical things about ESD projection... in the electronic class number of things were blown up in there for stupid things that actually should be protected (EEE, Hugo, Phase 1, 2019).

no one taught me how to start putting diodes for my power. And boom (EEE, Cody, Phase 1, 2019).

That is some of the simplest electronics design you can make that makes things a hell of more sustainable just by making it improved in design (EEE, Hugo, Phase 1, 2019).

According to Dehirm, EEE is a very broad field in which it is difficult to determine who is responsible for sustainability. He noted that, in order to be sustainable, the total number of components must be limited, and this must be done by a specialised designer so that the engineer knows what they are doing. He went on to say that he had no option but to use the products as an EEE in the industry. But it would be far better if product designers were held accountable and encouraged to include sustainability in their designs.

It'll really depend on where ultimately I end up as an electrical engineer, which is a very broad field. What I was doing previously, essentially, electrical design and PLC automation, there wasn't a lot that I could actually do. So even though it's design engineers, as a title, it's mostly a case of the process engineers having identified all the bits we want. You work out how to wire them together, and there is not actually a lot of room to input into the design. However, there are definitely other fields, you know, where that could be much more applicable. You know, if you're actually designing products from the ground up, you know, you're designing a circuit for PCBs, you could definitely make changes to, you know, make sure you reduce parts counts and things like that. But yeah, it's, uh, it's definitely gonna be a case of, you know, we're getting up and

what specific application do you go into? Because, yeah, it gets quite specialized (EEE, Dehirm Cilnal, Phase 3, 2021).

Dehirm gave more evidence to back up his claims about design and technology, such as the “design for environment” assignment, in which he investigated many techniques to improve the overall efficiency, design, and, of course, sustainability of the meat industry. He illustrates how smarter design in the red meat industry and agriculture, for example, may lessen environmental issues.

That was essentially about design, either designing a process or suggesting changes to an existing process to increase sustainability. Identifying, you know, sort of key factors of how to improve a process, which I did a little bit broader, I did it sort of for red meat in general. So I also looked at, you know, the agriculture aspects, animal rearing techniques, etc. Because, yeah, obviously, we’ve got a huge problem here with nitrates and different contaminations...(EEE, Dehirm Cilnal, Phase 3, 2021).

In the questionnaire, EEE exhibited involvement and enthusiasm with technology and the necessity of technology’s being available to everyone through reduced pricing. The following excerpt shows one such comment from EEE students.

Better developing technologies, making cheaper solutions for everyone (ST77, Electronics,QUS,2019).

EEE members were primarily concerned with technology and improved design, as seen in this section. Surprisingly, there are several concepts that may be classified as superior technology and design. One such example is the usage of automation, which will be described more below and was likewise highlighted only by EEE participants.

Automation

Technically speaking, automation might be categorised as a kind of technology. However, the influence of automation on the essential pillars of sustainability, as well as how EEE participants referenced it, make automation a significant concern when teaching sustainability. Dehirm was worried about the red meat

industry because he saw it as a major contributor to New Zealand's environmental problems, and he felt it was critical to completely automate the industry via the use of image processing and robots. Dehirm's idea is shown in the following excerpt:

Honestly, I think the only way I can see them making a meaningful change is to essentially completely automate the process, which, of course, will also have massive social implications of making, you know, a large portion of their work redundant (EEE, Dehirm Cilnal, Phase 3, 2021).

Dehirm discussed how technology has advanced and how a process that was once entirely manual is now a combination of automation and manual work. In the next ten years, he predicts, the industry will shift. The most crucial thing that sprang to mind after reading his extract was how critical it is to use smart design in the red meat industry. Due to the fact that not all beef cuts are identical, a completely automated method was merely an ideal until today, but with new computer vision capabilities, that dream could soon become a reality. Dehirm further explains why it is hard to fully automate all systems and why it is essential to create and design these systems with care. He explains:

Traditionally, it's been very difficult to do; we're talking about a process where there is a huge amount of variation, like, every single animal that comes through has a different size, has a different shape... It's been very difficult to make machines that are cost-effective, that can do that what humans can do. However, that's changing rapidly. Computer vision has come a long way. I was actually reading some articles, and it talked about a coronavirus epidemic in Europe... apparently there has actually been a huge investment in research over there. And automation, too, is already starting... it used to be an entirely manual process. Now, it's a mixture of manual labour and machines to do certain jobs. But there is still a heck of a lot of stuff that is done manually currently (EEE, Dehirm Cilnal, Phase 3, 2021).

Dehirm also made a connection between automation and its impact on social issues. On further questioning, he pointed out that automation does not have "one silver bullet" solution to the question of how to deal with social impact of

shifting to a new phase of industry management. Rather, there needs to be a more complex examination of both the “pros and cons”. This perspective raises some new questions, which Dehirm mentions as follows:

I mean, the thing is, most of these jobs I’m talking about are, you know, operator positions, or people who, you know, manually cut the meat or do other things. Those jobs will be, you know, basically replaced by machines... (EEE, Dehirm Cilnal, Phase 3, 2021).

In light of these concerns, Dehirm asserts that it is difficult to avoid automation, and that it is just a matter of time before systems adapt to the new demands. He continues, “I think, you know, we’re sort of at a tipping point. I think, five, ten years into the future, it’s going to be a very different industry.” Of course, because he has already demonstrated excellent system thinking regarding industry sustainability challenges, he raises the topic of how we must address both social and environmental sustainability issues together, as ignoring one or the other will be impossible. The industry will have to adjust its processes in order to adapt to the new sustainability goal, and then it will be a question of how society will react to this shift. The Dehirm extract shows his emphasis on considering both the environment and society to improve the meat industry:

I think it’s going to be a case where we have to do both. It’s, you know, like, say, the red meat industry, as it’s, yeah. We can’t keep it, the industry can’t stay the way it is, and... have any hope of meeting any of our sustainability targets? I think... mass automation is coming.... it’s a problem that, you know, society is going to have to tackle one way or another, but it’s, uh, yeah, I definitely think it’s, you know, it’s not going to be a case where you can ignore the problem, though. Like, it’s, you know, both challenges are definitely going to be tackled together (EEE, Dehirm Cilnal, Phase 3, 2021).

As previously said, automation may be a component of technology and design, but the impact it has on the social side of sustainability necessitated a separate section. In some ways, the influence of technology on the social and environmental aspects of sustainability should be more prominently displayed, and this is what EEE participants are attempting to express.

Mechanical Engineering: Modelling and Interpretation

Aragon's key point for finding relevance between sustainability and his discipline was using examples that related back to modelling and visualisation; he explained:

... I can clearly see how system thinking, cause & effect and diagrams are related to it... I think some of the fault trees and resilience diagrams I struggle to wrap my head around. Partly because a lot of them were similar, like some of them appeared the same, but they worked slightly differently or the philosophy behind them slightly different... (ME, Aragon, Phase 1, 2019).

Jenniye, as a newcomer to the field of engineering,⁶ had little experience with modelling and visualisation, a notion that practically all engineers must deal with. Of course, Jenniye did not find the visualisations appealing and she did not trust them, since she thought they represented a terrible lie designed to appeal to the masses and convince people to buy what each firm was attempting to offer.⁷ As a mathematician, she felt more comfortable with numbers than with graphs and visual aids to convey her work in the assignment. In the excerpts, she describes her view as follows:

See the mathematician in me, my eyes bleed at those moments, because yeah, but yes, you're right. But the difficulty is the people receiving this information and not knowing what it means and falling victim to my beautifully drawn graph, which is positioned in just such a way that I want you to see this as the biggest thing, and buy my thing because here it is. That frustrates the hell out of me because these are the people making decisions that impact us globally, literally. And I guess they are being taken in by somebody who's drawn a pretty graph, spun it around this way, and put it in three dimensions (FE, Jenniye Orso, Phase 3, 2021).

After being exposed to a visualisation application, Jenniye was able to organise the LCA and her ideas into consumable and easy-to-read boxes (a system

⁶Jenniye used to be a teacher.

⁷This is mostly about LCA, but she had problem with modelling that will be discussed later.

boundary plan) with a fixed theme, which aided in her comprehension of the paper content. As a consequence of our chat, she added, "I went home and created a bunch of charts because I figured that, if I could put my thoughts into a chart, I could grow my LCA out of it, which is essentially what I did." LCA weighed hard on her for a multitude of reasons, she couldn't make sense of it, and she felt as if she were "walking blindly." She conveys her disapproval openly in the following excerpt:

Yeah, the LCA, as I said, I, I had read and read and read and read your slides, and I had gone over and over and over what the steps were and what I needed to do. And then I get to each step, and I'd have no idea how to put that, how to get it into a small enough and organised enough mess that I could put it on a page...and the LCA, for me, I just felt like at each step of the way was walking blindly through it, I just didn't feel like it was, I had enough of any one thing to attach anything else to it. So, it just kind of felt a bit disparate and thrown together (FE, Jenniye Orso, Phase 3, 2021).

Modelling and visualisation, as indicated by ST87 in the questionnaire, may be utilised to aid in the reduction of material requirements in any mechanical design, hence enhancing efficiency and avoiding the need for frequent repairs:

For mechanical engineers to ensure the materials are being used effectively to improve the sustainability of the system and reduce the need for more resources to fix it (ST87, Mechanical, QUS, 2019).

The ME and CHE disciplines found comparable concepts connected to their respective disciplines, such as modelling, visualisation, and mass balance. The only reason they are presented in different sections is due to the amount of weight given to each idea.

Chemical Engineering: Mass Balance

Mass balance is a crucial component of modelling and visualization, as it aids in comprehending a system. However, participants' interpretations within their respective disciplines may separate these into different categories. Kairdra, for example, found her assignment on LCA rather easy and did not show any sign of trouble. This is however not true for the other participants, who all struggled

with the [LCA](#) assignment. According to Kaidra, the primary distinction between her and others was that she was familiar with topics already covered in the paper, such as mass balance and requirements engineering. As it turns out, [CHE](#) students take intensive mass balance and modelling classes as part of their degree, as she explains:

... It's like, because we have we had to do like mass balances and energy balances...system like intakes, out-takes and how much flow is going through it, and then we have to, like, design like heat exchanges ... So that we understand like mass balances to pretty much like build our process ([CHE, Kaidra Of Daevon, Phase 3, 2021](#)).

Another compelling argument for why mass balance is a discipline-bound concept for [CHE](#) can be found in Kaidra's frequent remarks regarding how mass balance aided her in her [LCA](#) project. For instance, "Yeah, I recall the [LCA](#) because I had to deal with all the mass balance and things." When Kaidra was pressed to elaborate on this comment, she stated:

... you can set system boundaries on your LCA and then analyse material flows. And then also, like, the risks of what you've decided on, on how that's going to affect the overall sustainability of what you're looking at, it's not just a user bias point of view, you have to also analyse how what you're considered, I guess, in the great third units you've considered would affect, you know, I guess, the validity of the statements and stuff ([CHE, Kaidra Of Daevon, Phase 3, 2021](#)).

The significance of how Kaidra ties the [LCA](#) different stages to mass balancing, modelling, and visualisation makes it discipline-bounded for [CHE](#). The main concept that helped Kaidra was mass balance, and she believed it was one of the concepts that caused students to struggle in the [LCA](#) assessment, as they could not comprehend it. She added, "I think so because I didn't worry about it. Like just from Zooms (class) and stuff, I think people were getting consumed about just a mass balance". When asked about her prior experiences with mass balance and modelling, Kaidra states, "Since second year till now, we are essentially dragging it out till the fourth year. However, we accomplished it on thermal paper as well." Additionally, as she puts it, "I believe so. Yeah. Like,

we're pretty confident with our units and stuff." Further discussion with Kairdra showed that understanding mass balance can help with designing [LCA](#) system boundaries. As she explains in the following excerpt, understanding mass balance could make one of the hardest assignment in the paper much simpler:

Yeah, I think so. Because then it gives you like a border for, like, an overview of it. And so you can, so, when you go to design something, you know, you can, like, think about it, like it, the LCA points out, like, a lot more than what you think on just a surface basis, I guess. So just, like, because even it can consider, like, depending on your boundaries, energy in your feedstock and rice and you can just see how much waste can be taken and change it, I guess ([CHE, Kairdra Of Daevon, Phase 3, 2021](#)).

The key concept that assisted [CHE](#) participants with [LCA](#) was mass balancing and modelling, as stated in this section. [LCA](#) will be highlighted more in the next section, as will the link it has with all disciplines.

4.2.2 Shared Concepts for Engineers

General Concepts are the basic concepts shared by all disciplines. The manner in which participants used these ideas in this study demonstrates their significance to the broader understanding of sustainability education. It is important to point out that the term general concepts does not imply that all disciplines share the same knowledge. As this section indicates, each discipline has a unique understanding of each general concept. However, since these notions were referenced by two or more disciplines, they have been included here and separated from [previous section](#).

Fault Tree Analysis: Risk and Mitigation

A notion mentioned by majority of disciplines in this study was “fault tree analysis,” also known to the participants as the “functional block diagram.” [Fault tree analysis \(FTA\)](#) is a tool for analysing the likelihood of system or machine failure by graphically and mathematically depicting the system. Condan and Thaddeus explain fault tree analysis as follows, emphasising its significance and how it might aid in risk assessment and mitigation.

... using fault tree analysis. With a backup plan and a look at existing or future possibilities, we can proceed with confidence... and can look at the potential exist in the project ([CE, Condan, Phase 1, 2019](#)).

You can predict whether or not an accident will occur using the fault tree, and if it does then, using resilience, you can create a backup plan or reduce the damage, if necessary ([MP, Thaddeus, Phase 1, 2019](#)).

Aldona also mentioned how risk assessments and fault tree analysis are beneficial, and also hinted at the relevance of the concept in her discipline, specifically because it has shown her how a small mistake by engineers could result in the destruction and deaths of many:

Well, I found that the mitigation process is really good and how to actually clean up after something was built so that the environment is not affected. And as well as a lecture that they showed

us previous disasters cause it kind of showed me, like, make sure everything stays updated and everyone knows the correct procedures. That was scary as well to see something, like, would happen just because procedures were not followed (CE, Aldona, Phase 1, 2019).

FTA is notable for being seen as relevant and beneficial; even EEE participants felt FTA to be relevant to their disciplines. The example of relevance mentioned by EEE students was “Boolean Logic”, which was taught in the first year electrical and electronic paper. The following extract explains why FTA was deemed the only beneficial topic in the sustainability paper by EEE participants:

It was Boolean logic (EEE, Hugo, Phase 1, 2019).

Yeah, we learned those in the first year. And that should have been introduced in the first year (EEE, Cody, Phase 1, 2019).

We remember the functional block diagram, because it is was and/or gate. We did that in basic introduction to electronics and electricity in first year (EEE, Hugo, Phase 1, 2019).

Dehirm chose risk analysis and hazards analysis as advantageous because he was already familiar with the ideas through his work-mandated classes. Dehirm explains in the following excerpt how the risk analysis was beneficial since it allowed him to reflect on his past training; yet, as he points out, it was not its difficulty, but rather its familiarity, that enabled him to recollect what he had already learned.

Things like the hazard analysis were very familiar territory for me because I’ve done a fair bit of health and hazards courses and analysis courses and things... (EEE, Dehirm Cilnal, Phase 3, 2021).

Additionally, Dehirm points out that risk analysis has various similar titles and all refer to the same principles. In the following excerpt, Dehirm summarises the primary use of failure mode analysis and notes that it is, in some ways, a requirement that every line engineer should be familiar with it: “Protect what you can,” he added.

...there are various names...but they all tend to mean very similar things. Like, one thing I’ve actually done was a two-day paper for

Functional Safety, a technician paper, which is basically looking into machine safety, which basically boils down to, you know, trying to put guards on things where you can, adding interlocks and things, but you use a lot of the very same methods that you use for any other sort of hazard analysis. You know, it's, yeah, there are different techniques, there's different terminology, but they all boil down to the same basic concepts ([EEE, Dehirm Cilnal, Phase 3, 2021](#)).

Dehirm's post also brought up by Aragon and other participants. Aragon, for example, that mentioned the only beneficial topic was FTA, to which he could easily relate. He not only learned about FTA in his previous papers but it was also something he had to use in his summer job.

If they give me, let's say, functional block diagrams, definitely comfortable with those... actually, that is a good thing to point out the failure mode and risk analysis. I actually had to write those in my summer placement last summer. So, it was useful to learn a little about that. So, I have personally used those in my work placement before. All these AND & OR gates I am familiar with from electronic. It is something we can all relate, that was actually easier to understand ([ME, Aragon, Phase 1, 2019](#)).

[SE](#) participants also agreed with Dehirm and Aragon and found FTA to be beneficial. However their reasoning, as pointed out by Meinrad, is closely related to software engineering requirements, but also to safety and redundancy plans as previously described by Dehirm.

I think risk and resilience, [you can hear some people agreeing to] I think you can apply that to make sure your software got redundancy set up; if one part fails the other part will pick it up ([SE, Meinrad, Phase 1, 2019](#)).

I was going to say risk analysis ([SE, Tancred, Phase 1, 2019](#)).

Yeah, it could be said for both fault tree and risk analysis ([SE, Raynard, Phase 1, 2019](#)).

Life Cycle Assessment

A majority of participants from all phases in this research mentioned and focused on [LCA](#) since it was one of their key evaluations for the sustainability paper. Interestingly, while [LCA](#) was mentioned by all disciplines, it was not treated as a similar concept. There were a few disciplines which had fewer issues with [LCA](#), while some others found it hard and tedious. For example, Kairdra was one of the participants who discovered the benefits of [LCA](#): “I thought the [LCA](#) topic was useful,” she stated. As seen in the following excerpts, she describes how intriguing it was to learn about plastic and paper cups and their impact on the environment. In a sense, becoming aware of the distinctions between things we use on a regular basis, and discovering that the process is not as straightforward as one might believe, can only be learned by [LCA](#).

Yeah, like some of the big basic concepts around stuff, like we’re just looking at the differences between a plastic cup and a cardboard cup. And you know, just to make you aware, I don’t know the differences and how it’s just not a straightforward process ([CHE, Kairdra Of Daevon, Phase 3, 2021](#)).

Kairdra discussed in the interview the primary reasons she finds [LCA](#) valuable and why she is interested in the manufacturing processes of various items. As seen in the excerpt below, Kairdra brings up several critical aspects of the [LCA](#) procedure that every analyst who wishes to prepare a report must fully comprehend. In her opinion, what made [LCA](#) useful was establishing a clear system boundary by examining a product’s many life cycles, assessing it with a material flow diagram, and calculating its sustainability effect using various materials and techniques. Furthermore, as evidenced by her extract, Kairdra found the system thinking component of [LCA](#) to be extremely beneficial.

Because you’ve got that whole cradle to grave, cradle to grave against cradle wherever you want. And so, like, you can set system boundaries on your [LCA](#) and then analyze material flows. And then also, like, the risks of what you’ve decided on and how that’s going to affect the overall sustainability of what you’re looking at, it’s not just a user bias point of view, you have to also analyse how what

you're considering, I guess, in the great third units you've considered would affect, you know, I guess, the validity of the statements and stuff (CHE, Kairdra Of Daevon, Phase 3, 2021).

Additionally, Lannis picked the LCA topic as the most beneficial in the sustainability paper. "EIA and LCA were new to me, and I had never done anything like it before. That is why, these were most beneficial", she remarked. She was unable to articulate what made it useful and simple for her, but she might allude to an idea described by Kairdra in the preceding paragraph. As seen in the excerpt below, Lannis discusses her ability to link boxes and her proficiency with modelling and the interpretation of models. This capacity might be linked to material flow analysis and the system boundary analysis used in life cycle assessments. Aragon, like Lannis and Kairdra, found LCA easy and straightforward: "LCA is pretty straightforward for me. The whole purpose of the LCA seems very clear. The whole philosophy behind it was pretty simple... I understand the general info".

The organization of ideas is something that I think other people struggle with and that I think I'm quite good at. So, like, you had to be able to put everything in boxes and address what box goes where and what goes in that box. And I feel like I can already do that from my previous teaching experience. Yeah, but if you didn't have that going in, and you just got given all these ideas and you didn't have any idea on how to arrange them, then you probably didn't do that (ME, Lannis Krun, Phase 3, 2021).

When it came to LCA, not all participants agreed with Lannis, Kairdra and Aragon. SE and EEE participants found LCA to have no relevance to their fields. Furthermore, LCA was not perceived as simple or useful by the other participants. Participants discussed their thoughts on LCA's difficulties and its tediousness in the following section. However, because this study was conducted in different phases, and Phase Two participants were first-year engineers, their perception of LCA was reported first, followed by third- and fourth-year engineering students.

Life Cycle Assessment for First-year Engineering Students: Troublesome and Transformational

It can be observed that most students regarded [LCA](#) as troublesome in general. Additionally, they identified boundary and boundary selection as one of the most challenging aspects. Of course, they drew attention to the difficulty in estimating and conducting research. They also mentioned how time-consuming it was to hunt for information on the internet. Corwin exemplified their frustration:

For me, the one difficult thing for me to do was the search for scholarly sources that I can use to aid me in this project. It often felt like my search queries went nowhere at all, sending me in a loop of finding articles and data that wasn't quite what I needed... Over time my frustration had grown to the point I had to step away from the computer and do something else to calm down... Though I must admit that sometimes it's hard to trust my sources and it makes me wonder if I have cited them correctly ([1st year, Corwin, Phase 2, 2020](#)).

Ervin continues on the theme of the challenge of doing research and collecting data, and also emphasises that he/she overcame this obstacle by honing their research skills:

The most troublesome aspect of the project for me was finding information from reliable sources to support ideas that I had... I was pretty certain that there would be negative environmental impacts associated with discarding concrete; however, it proved difficult for me to find reliable resources with information that supported this idea... ([1st year, Ervin, Phase 2, 2020](#)).

Of course, not everyone struggled with research and data collection. Joyab, for example, struggled with the report's word restriction and was unable to satisfy themselves with the report's content. As seen in the following excerpt, Joyab noted how he/she had to return to the task numerous times to get it perfect and satisfy themselves:

What I found most troublesome to understand and do in this project was determining the amount of work that I should actually do to fulfil the project requirements ... I had to continuously spend time

removing aspects to get below the word limit (1st year, Joyab, Phase 2, 2020).

Treowe is the sole student who encountered technical difficulties with LCA, and this problem points to another aspect of the Troublesome theme. Treowe described how difficult it was to determine the precise material input and output for the project (this step is what we call inventory analysis for LCA). As seen in the excerpt below, Treowe encountered difficulties determining the project's mass balance:

When calculating the mass of the two designs, I found it difficult to rationalise the weights calculated. Although I understood my calculations, I did not have a full understanding of the relative weight of the materials and how this would turn out in my final calculations. Through further research, I was able to justify my calculations and develop my understanding in the shear mass of materials that go into a project like this (1st year, Treowe, Phase 2, 2020).

Treowe's extract clarifies what all students are discussing and directs our attention to Boundary as the most perplexing component of LCA. A critical part of LCA is boundary selection, and if the boundary is not precisely chosen, it will generate distress and lead students to search for answers, as demonstrated in the student extracts above.

Only a small proportion of students will be able to get around this by estimating and assuming numbers for their LCA assignment. Consider the following quote from Pin, who explains how assumptions and estimation are critical for engineers in order to save money and time:

This is an essential ability for engineers as often time and cost restraints mean in-depth and accurate lifecycle assessments are not possible, resulting in making assumptions, and this helped gain more experience so will become easier (1st year, Pin, Phase 2, 2020).

During their comments, Pin also mentioned how getting data was challenging and unpleasant for him/her, but Pin was able to overcome this by using assumptions and estimation, much like professional engineers would:

At the start it was extremely frustrating not having all the information, but this made me understand that as an engineer you are not going to be given all necessary information, but need to use logical assumptions and estimations to provide the most accurate assessment possible (1st year, Pin, Phase 2, 2020).

As previously stated, the predominant concern was with academic reports and research. However, that worry became a transformative experience for the students, and of course, being a first-year student exposed students to the world of engineering and educated them about sustainability and how it can be used as an engineer has its ups and downs. Corwin eloquently displays this shift by revealing that he/she had believed engineering was entirely about mathematics and computation, but instead has spent the majority of his/her time hunting for data and participating in solving problems:

This project has had a vast and adverse effect on my understanding of what an engineer does. I followed what I believe to be a common preconception within this paper: that engineering was just applied science and math and, thus, my work would be along a similar vein to that. Yet what I had discovered during the writing of this report and all the research that went into it, less than 10% of this project was actual mathematical calculations and the actual 'practice' of what I considered engineering. Most of my time was spent researching other people's articles and interpreting them for use within my project... It was important to learn and understand the role of an engineer through practice, which is in line with my way of learning best (1st year, Corwin, Phase 2, 2020).

Another transforming feature of the paper that altered students' perceptions of engineering and real-world sustainability challenges was the realisation that not everything is as straightforward as it appears. In other words, despite the fact that students had access to all data and the assignment was simplified for them, it took them weeks to complete. Joyab makes the following point:

This assignment transformed my ability to make assumptions and estimations when not given enough information to make in-depth and accurate assessments... At the start it was extremely frustrating not having all the information, but this made me understand

that as an engineer you are not going to be given all necessary information, but need to use logical assumptions and estimations to provide the most accurate assessment possible (1st year, Pin, Phase 2, 2020).

Environmental concerns were also a concern for students. They showed their support for the project's contributions to environmental and sustainability issues. Students' perceptions of engineering projects have shifted significantly as a result of the report's environmental implications. It was only after doing an LCA that they realised how big of an impact a small undertaking might have on the environment. They grasped the nuances of how things actually function in the real world. Treowe illustrates this in the following way:

My discovery of the sheer amount of greenhouse gas emissions produced by a single project really affected the way I looked at engineering processes and the importance of pursuing sustainable options in large projects such as this one... was eye opening and helped develop my somewhat limited knowledge of the environmental side of engineering (1st year, Treowe, Phase 2, 2020).

With regard to environmental impact, Ervin was able to relate it to the economic viability of waste management by employing system thinking. It's amazing to observe how first-year students relate to system thinking, even if it's not as prevalent as in subsequent phases of study.

... which in some cases can also improve economic feasibility by reducing waste (1st year, Ervin, Phase 2, 2020).

However, there were a few instances where students indicated how uneasy they felt. Their inability to comprehend estimation and assumption contributed to their feelings of ambiguity. Joyab suggests his lack of technical expertise is to blame:

I can't really make any estimates because I have no technical knowledge in the field (1st year, Joyab, Phase 2, 2020).

However, Joyab also shows signs of uncertainty regarding other aspects of LCA, such as environmental impact. As mentioned in the following extract, this uncertainty is related to a lack of knowledge regarding LCA system boundary selection, which was a common issue among all students.

... so I'm confused about what environmental impacts we are expected to take into account... so I'm confused about what stages we are expected to do in our LCA (1st year, Joyab, Phase 2, 2020).

Ervin also shows signs of uncertainty by indicating that he/she is not sure about what is required to be included in the different stages of LCA. Yet again, this is a sign of lack of mastery when it comes to LCA boundary selection.

I find it quite difficult to find the specific, detailed information required to properly complete a life cycle assessment. For example the carbon footprint associated with a specific material or with a specific vehicle involved in the transport and distribution of the finished product (1st year, Ervin, Phase 2, 2020).

Life Cycle Assessment for Third-year Engineering Students: Troublesome

For third-year students, the data suggests that the LCA was the most difficult component of the paper. Reasons for the difficulty differed between participants. For example, Thaddeus struggled with LCA since she wasn't sure what she needed to do: "Since we have no idea what we need to do for it". "I'll say the LCA was the one that I struggled with the most," Dehirm added. In the following excerpt, Dehirm continues to explain how LCA's broad scope and the level of detail required have made it a very difficult task. He further added this was not solely his individual problem, as "a lot of people bounced off it." According to Dehirm his work suffered significantly due to all the assumptions that he had to do. As shown below, he did not liked the result at all:

.... mainly just because the scope is so broad, and yet, at the same time, it needs to be so detailed. I basically just cut and cut and cut so I could, you know, get it to a manageable scale. And, you know, the results suffered because I basically sat in it, like, there's no point even trying to do a sensitivity analysis here, because basically, my data is complete garbage. I've made so many assumptions that this is, you know in terms of actually being a meaningful report, not so much. You know, I definitely noticed from other students that they struggled a lot, too... (EEE, Dehirm Cilnal, Phase 3, 2021).

A few keywords that Dehirm associated [LCA](#) with are “broad scope”, “detailed”, “dense topic”, and “jargon terms”, as illustrated in below. Additionally, Dehirm recounts how each step he made in search of an explanation contributed to his confusion, and the amount of intricacy is evident in his excerpts. As Dehirm stated, one example of the complexity is the solar panel recycling technique, which is complicated by the fact that there are several solar panel models and recycling methods:

... a very broad scope, is very detailed, and a very dense topic. And there are a lot of, sort of jargon terms, that you have to sort of learn to sort of get what it's getting at almost under... what I found was, you know, every time I try and research something... I was looking at recycling plants for solar panels. And I found out that there are about three different types of solar panels that have completely different processes and need completely different techniques to do them. And I was like, I ended up cutting out two or three of those three because I couldn't find data. But yeah, it's like, everything you look at, the complexity just keeps exploding ([EEE, Dehirm Cilnal, Phase 3, 2021](#)).

According to Dehirm, the key cause of the challenging element of [LCA](#) is its interconnected nature, where a basic process contains a lot of hidden or undiscovered activities. Dehirm expresses his overwhelming experience when he first began studying about [LCA](#), as this was something he had never done before:

... there are just so many factors and that they're so interrelated... It's, you know, to identify something that's, you know, a seemingly simple process has wide-ranging effects, but, you know, identifying and categorising, it's definitely, I definitely, been quite different to what I've done in the past. And I did find it, you know, in the beginning, quite overwhelming, you know, just trying to get a handle on that complexity ([EEE, Dehirm Cilnal, Phase 3, 2021](#)).

Dehirm admired the [LCA](#) process and had a favourable attitude towards it, even though “it was the one that I struggled the most with”. He saw the significance that the [LCA](#) could have if utilised correctly. However, in his assessment, he was unable to discover any correlation with the work he had submitted because the work contained so many assumptions. Dehirm recognised that this was

mostly due to the assumptions' limitations, and that a genuine [LCA](#) would almost certainly include real data.

...again, it was the one that I struggled the most with. So I probably got the most out of learning how to overcome it. Like, I will, I'm, I've still got some doubts about the effectiveness of like, like, with my experience with it, you know, I found I had to make so many assumptions. I understand in a real LCA, you've got a lot more time and a lot more resources to actually get data to fit on a lot of those blanks, but just due to the fact that you're talking about a system with so many inputs, so many outputs, so much inherent complexity, there's bound to be a lot of assumptions in there, which I believe that's why part of the SEO progress is documenting all your assumptions made. And it's, I guess it like, for all the, like, the effort until, it's still basically just a snapshot, isn't it? But it's, you know, it's still definitely better than nothing at all ([EEE, Dehirm Cilnal, Phase 3, 2021](#)).

Jenniye, like Dehirm, thought the scope of [LCA](#) was too vast; she likened it to infinity, where there is no end. She went on to say, as illustrated in the following excerpt, that it is entirely up to the individual doing the study to decide where to stop and how to control/stop the effects on the environment. Jenniye found [LCA](#) difficult because of its broad scope and detailed description that it required.

I'm doing an LCA ... I'm looking at a point under a microscope. And that's actually completely irrelevant. What's relevant is where it is, what's happening at that point, and what is influencing what's changing it... because then you see the big picture. The picture goes on to infinity with this stuff, and what you can look at in environment goes on to infinity, because I can be looking at sustainability. And I can be looking at a specific project or product development in light of what it's doing to the honeybees, you know, out here, or you can be looking at it from what's happening to a waterway, what contamination is going on there. Somebody else can be looking at it in terms of what kind of seismic influences are operating ([FE, Jenniye Orso, Phase 3, 2021](#)).

Further conversation with Jenniye elucidated the source of the difficulty in [LCA](#) for her in particular. Jenniye and Dehirm both believed they performed poorly on their project, they even comparing their work to “garbage”. Jenniye, like Dehirm, found it infuriating that the information she sought was unavailable, and she was forced to make assumptions and approximations. Jenniye employed the rabbit hole analogy, as seen in the following excerpt, which details her effort to gather knowledge regarding the assignment she was assigned. “I’m drowning in data,” she added:

The LCA I hated because I thought I’d done such a bad job of it. And I felt like it was like us being expected to write a symphony ... I felt frustrated that I didn’t have access to the right information, and that the information I found couldn’t verify the technical truth of it and they would be things that talked about an input of a certain chemical, and then there was no reference to its output anywhere or where it went or what was going on. And then I’d go, you know, it’s like if we go down the rabbit hole with these things, and you click a reference link on an article, and I probably at one point, I was 46, or 47, reference clicks away from where I’d started trying to find a line up the Swiss cheese. So, I could actually put a line right through it or and I couldn’t; I found that really frustrated ([FE, Jenniye Orso, Phase 3, 2021](#)).

Yell stated, “I think I understood the concept of [LCA](#), but choosing a system boundary was a bit challenging”. Jenniye and Dehirm also addressed the problem of the system boundary in [LCA](#); they both struggled to condense the scope of the assignment. In certain ways, the more precise and narrower the system boundaries become, the more difficult it becomes to acquire data. Both Dehirm and Jenniye had felt dissatisfied and bewildered due to the depth and complexity of the [LCA](#) system boundaries, as Jenniye described:

But when it came to data, and you know, I kept using this one source because then at least vaguely my inputs and outputs might appear to come from the same source rather than, you know, which was really tricky. And this, in fact, the smaller you made your system boundary, the harder it got. Because you had to be so much more specific about what was going in and what was going out.

So, and it was just a really uncomfortable process there (FE, Jenniye Orso, Phase 3, 2021).

Yell points out the complicated procedure when it comes to LCA, with comments that implied the system boundary was the challenge, and noting how it is frustrating to know where to stop or whether he has provided too much or too little information. Jenniye and Yell are both concerned with scope of LCA as Yell describes.

I think sometimes I was like, 'How deep to go? So this metal was used in the tractor. Ok, how's that metal mine? How much energy is used to get those metals?' Like smelting the metals decay, you can just keep going basically to get them and if you talk about a whole life cycle, their whole LCA is very complicated (SE, Yell Davurson, Phase 3, 2021).

Dehirm echoes these points: "...with LCA, I found a way to look into something, and what I thought was basic thing, turned out to be a complex system made of many other systems". Dehirm expands on his statement, Dehirm expands on LCA and system thinking by mentioning that:

System thinking is obviously, well, that's essentially what the LCA is: trying to have an impact on the whole system. I mean, I don't really see design as, I guess, something that's, like, designing how you're going to do your report and things. But I think it's, you know, trying to grasp the system aspect of it is probably the biggest part of how I would see the LCA (EEE, Dehirm Cilnal, Phase 3, 2021).

Additionally, Jenniye also found the inventory analysis rather hard. She struggled with the amount of detailed information and numbers that must be considered. She expressed her frustration:

... we had our inventory, I found out the life cycle of inventory really, really, really hard because it was so difficult to actually bring it down to so many grams of this, to put out so many grams of that (FE, Jenniye Orso, Phase 3, 2021).

However, not all participants were having difficulties. For example, Kairdra found LCA easy and straightforward. Kairdra explained that the major reason why she

wasn't as lost as some of participants was because of the "scope", or the boundaries of the system, that had been properly selected. As seen in the following extract, she had no issue with assumptions, system boundary nor inventory analysis:

... I think I set my boundary, so I knew that I wouldn't have to find too much data... But then I just do little things like try to find how much fuel consumption a digger takes or an excavator takes. It just takes time that you know that the teacher doesn't care if a number is right or wrong. And I just assumed a whole lot, but then, when you look at your numbers and you do the balancing, you're like, "Oh my goodness, that looks so wrong". You'd go back and change all the little things. So I guess maybe if it was easy, because a lot of people might use transport and stuff, if you guys just had a set number of arbitrary numbers that they could use. So you're not spending time trying to find little things, and they can actually go find the proper numbers if you know what I mean (CHE, Kairdra Of Daevon, Phase 3, 2021).

Lannis also did not find anything challenging, but commented on how she noticed where people had problems with system boundary selection: "The LCA was, I think most people struggled with what scope are you going to take, like where you're going to define your boundary".

Life Cycle Assessment for Third-year Engineering Students: Tedious

The tediousness of the LCA was a point on which almost all disciplines could agree. The procedure, the calculation, the whole of the project, and what was expected of them were described as tedious; in fact, the main source of LCA's being troublesome was its tediousness. Raynard commented, "...it was easy to grasp but I am not going to use it ever again". Tancred further added that LCA was forgettable and there was no way for him to connect it to his discipline. He mentioned that he found applying other aspects to his discipline easy, but not when it came to LCA:

I would say, if it came up again later, I definitely understand what it is talked about, but I don't think I would be able to start a conversation about it. It is forgettable; that is what I am trying to say... (SE, Tancred, Phase 1, 2019).

Jenniye also could not find anything conceptually hard with LCA; the challenge was more about implementing.

Nothing was difficult academically. But applying that understanding was difficult. Like it was. Nothing was difficult academically in terms of because so much of this is applying scientific principles to common sense (FE, Jenniye Orso, Phase 3, 2021).

Certain disciplines found LCA to be more tedious than others. For instance, while undertaking the LCA procedure for his forestry project, Yell described how tiresome the procedure was for him. According to him, the steps he was required to complete were particularly onerous for a software engineer. He noted that it seems usual for other disciplines to deal with environmental elements of LCA; however he felt uncomfortable with the approach:

Finding the data, putting it in a table and then saying this is how much energy was used. This is how much carbon was released. But the effort that's required to do that, especially because it was not just one tractor, if you're talking about forest harvesting, we'd have chainsaws, and other stuff, nine different machines. And then we had to do it for each one... It was tedious. I mean, I can't speak for other disciplines; maybe that is the way that things are done for them. There are environmental engineers, chemical engineers; maybe they have to analyse, do an analysis like that at the end of the day. But for software not so much... (SE, Yell Davurson, Phase 3, 2021).

Interestingly, despite finding LCA beneficial, Kairdra also found it tedious, in particular because she had to spend a lot of time looking for data and racing against the clock to complete her work. The frustration of being unable to locate the correct data and running out of time made the experience extremely exhausting:

Because... it was just so long. And then I just couldn't find data for ages. And then I had to write it up. And then by the time I

got to writing it up, I was kind of like sick of it, if you know what I mean, because you just spent so much time just going in circles with it. I don't know... it was a little bit unclear how to complete it. And until you get frustrated, and then you have to go hunt for your data. And then yeah, just like hunting for data is hard enough. And it's you just getting even more frustrated. And then, by the time you have to go write it up and read all the ISO standards, you're just like, well, there's a lot to do. I mean, time's running out. And so then you get stressed and then you don't enjoy it (CHE, Kairdra Of Daevon, Phase 3, 2021).

Even though participants from the majority of disciplines struggled with LCA, it was not conceptually challenging for them. As Dehirm explains in the following excerpt, once he got used to the terms, the remainder of the task was straightforward. He described the LCA premise as simple, and stated that the only difficult aspect of the procedure was his unfamiliarity with the system he was researching. This applied even to the terminology that he found difficult, as a result of the subject he was researching for his LCA project:

I don't think so, once you get it, because there's that there's a lot of sort of new jargon and terms, which you, all sort of hits you at once. And so you're just taking a bit of time, I think, to internalize, you know, you know, understand what it's talking about, like, yeah, it's a, I guess it's one, like, I don't think there's an easy way to break it up into smaller parts and tackle it piecemeal, which is my typical technique. So, you know, like, that tends to be, you know, how I work on difficult concepts, with this kind of feels like you've kind of had to learn a whole bunch of stuff at once. And then, once you get it, it's fine. But you know, it took a bit to get to that point (EEE, Dehirm Cilnal, Phase 3, 2021).

According to Jenniye's arguments, everyone was pessimistic, since they all assumed they would fail the LCA assignment, imagining that they had underachieved, and worrying about their grade. Even though she achieved a high grade for her project, she lacked faith in the assignment:

... And I really thought, I mean, when I was waiting for my LCA grade to come back. I thought I had failed this so badly... I could

not get pictures on it, or I just felt really like I was doing a rubbish job of it... I wasn't the only one, everyone was going, oh my god. How would you do it? And that was rough... (FE, Jenniye Orso, Phase 3, 2021).

Life Cycle Assessment in Software Engineering

Software engineers and LCA had a one sided relationship; none of the SE students thought LCA would be beneficial to them. Tancred and Raynard elaborate on this point by stating that LCA is unnecessary for them because they are developing software, and the only thing they need to consider is their office hours and possibly the energy usage of the server and computer they are using:

Yeah, I don't see how we can apply it, like LCA for developing software would be people showing up to the office (SE, Tancred, Phase 1, 2019) and write code (SE, Raynard, Phase 1, 2019).

They all have computers, maybe a server room, leave the computers on for 8 hours a day. Or maybe servers are always running (SE, Tancred, Phase 1, 2019).

Even Aldona from CE confirmed Tancred and Raynard's statements. She questioned the integrity of the work they are doing for LCA, as it has no relation to SE whatsoever. According to Aldona, her group was mainly concerned with carbon emissions from traffic light installation:

... The problem is LCA because there is not any LCA when it comes to the program on the computer... But at the moment, we are looking at the cars' carbon emissions and the carbon emissions of traffic lights... but what does the traffic light have to do with software? (CE, Aldona, Phase 1, 2019)

Pyrrhus did not find the LCA technique being taught to software students beneficial: "It serves no purpose for us". He advised that students be introduced instead to contemporary issues such as data centres, artificial intelligence, and machine learning, as well as how each of these energy and power consumption sources could be made more sustainable:

... you can see the data centres consumes a significant amount of energy and power. Like, and this is something that's completely diminished, is like, and this is on an, on huge exponential growth. So you're going to be seeing more and more as we're relying more on all of these AI and machine learning... these services need to run somewhere, and they consume electricity. And how is it possible to not care about something like that? (SE, Pyrrhus, Phase 3, 2021)

When asked whether students should be taught environmental engineering, Pyrrhus responded, "You could, but I'm not going to let it". His argument, as illustrated below, is that software engineers should concentrate on the concepts that are critical to them. Raynard confirms Pyrrhus' statement by noting that, "... We have not been introduced to environmental studies whatsoever so far at all". Pyrrhus argued:

because I don't have space like they need to learn software engineers, need to learn Software Engineering and Computing. We don't have the time to teach them environmental engineering or space for it (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus believes that software is a significant source of CO₂ emissions. As he puts it, "I believe that software engineering and software execution play a significant role". As he emphasised further, the contradiction in his views stems from his belief that students are taught how to solve civil engineering issues, but are not taught how to handle a project relevant to their own field:

So I'm not sure exactly what they're covering, but we cannot spend time teaching them about how to build better bridges, or how to build aqueducts or how to build filters...you have the Engineering Society, Engineering business and Engineering in environment, these three are the things that need to motivate towards it, but we don't have the space to do anything more than that...I think we're at the stage that...we have reached the point that you don't even need to cite, or you don't need to explain that humans are messing up the planet. And consequences have already come to haunt us (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus argued that there was a way to make [LCA](#) effective and make sense to students, while teaching it to software engineers. As he says in the following excerpt, software systems are divided into two phases: design and operation. However, unlike other types of engineering projects, software needs continuous maintenance. That upkeep is distinct from the design, development, and operating phases. As he stated, software undergoes numerous maintenance loops until it is retired:

... it would cover these two angles that I said earlier, because then you have in the beginning the design phase. And then you have the operation phase of software, like everything else. So unlike other, most other, types of engineering, where maintenance is something that happens infrequently, in software engineering, maintenance happens very frequently, like you get new versions of code every now and then, which means that there's new design work that's required in order to push the new maintenance, the new version up. So you have these very rapid cycles that produce new things. So what you will notice is that there is an initial design-only cost, and then you have these operating costs. And in parallel, you have another design cost, which pushes updates to the system all the time until you decide at some point to retire the software. And then you have to take into account retirement costs ([SE, Pyrrhus, Phase 3, 2021](#)).

Interestingly, when software reaches the retiring stage, which is comparable to the end of life for other items, it is not truly destroyed. As Pyrrhus explains and illustrates in the following excerpt, software simply becomes unsupported when it is no longer maintained. It is potentially available, but there will be no updates or customer support. A excellent example would be vintage console games or previous versions of Windows. Anyone may use it or possess a physical copy, but no assistance will be provided:

So in software that runs on your own machine, this is something that might never retire; its operation might not retire. So you have your favourite Super Nintendo console from the 80s or 90s, and you still run it, you will still be incurring this kind of operational cost. But what we mean by retire is that it was no longer going to

be supported; there's going to be no new versions coming up. But you know, this is the traditional thing (SE, Pyrrhus, Phase 3, 2021).

The latest approach to software retirement is accomplished using a cloud-based system. The simplest approach, as Pyrrhus explains, is to shut down the servers. If Google, for example, decides to shut down, there will be no Google search engine capable of handling user queries:

And nowadays, this is the way thinking like this is thinking the way of the 90s. Like software doesn't operate like this anymore, all of the software is practically on the cloud. So what we mean by the software being retired means that its server goes down, essentially. So it's no longer available, or it's been upgraded to something else. So you know, you go to google.com now, and you're able to Google. Like, if Google decides to retire its search engine, you'll go to google.com, he will say no, it's not there anymore. That will be software retirement (SE, Pyrrhus, Phase 3, 2021).

Like anything else, software retirement is not as straightforward as what has been explained, because of the hardware problem. The fact that software is based on hardware is what makes this case so intriguing. In a way a software engineer needs also to be knowledgeable about computer engineering. Familiarity is crucial when it comes to resource management (as will be discussed later when exploring provisional management). Pyrrhus highlights some of the issues posed by hardware:

The servers might be there, might be repurposed, or they might reach the end of their useful life, and they might be retired; the hardware is retired at this stage because you have the computer and computing side of it. Like, software engineering is interesting because it also deals with the management of these computing resources. So yes, there is an actual point that you do provision physical resources, and you do get rid of them. So, like, the computing aspect of it is something that we need to be taking into consideration as well because the software runs on top of computers. So this travels a bit on Computer Engineering. But given that we don't have computer engineers, the closest person who would be doing this is a software engineer. So a software engineer would

need to learn a bit, if not everything, of computers and computing engineering ([SE, Pyrrhus, Phase 3, 2021](#)).

4.3 Engineers' Perceptions of Sustainability

Participants' perceptions aid in examining the understanding of sustainability in engineering across many disciplines. The findings in this section aim to provide a comprehensive picture of participants' perspectives on sustainability in their personal and professional lives. Findings are also provided on participants' perceptions of sustainable engineering education, as well as perceived barriers to the implementation of sustainable development in undergraduate engineering programs. Within this section, a few essential themes are introduced that could help with understanding how participants connect with sustainability by creating certain concepts that are bound within their disciplines. Therefore, the critical finding in this section is the interconnectedness of all my findings. This interconnectedness allows me to reflect on how engineering, as a discipline, provides opportunities and barriers for the profession and for education in sustainable development in undergraduate engineering programs.

4.3.1 Engineers' Perception of Sustainability in Industry

Even though the majority of participants in this research were full-time students, a few were working in their respective engineering fields. According to participants, not all organisations follow sustainable initiatives, and the main reason is management. Moreover, the majority of participants had no expectation of being able to contribute to their company's sustainability decision-making. As a result, they were less enthusiastic about learning new concepts in the paper on sustainability. For example, Aragon mentioned that he has no hope of being able to contribute to decision-making in the industry as a junior engineer. He understood the decisions related to sustainability would be made by top managers and leaders. Therefore, he believed studying sustainability was idealistic, as he would not be able to do much anyway:

... but I am not necessarily the one making those bigger decisions. That is the problem. I was taught this stuff, and I might eventually reach the management tier and be able to use these, or I might even have my own company, but at least the people above me see in their own way. And I don't see how much I can do (ME, Aragon, Phase 1, 2019).

Dehirm also emphasised his standing as a junior engineer, how it has prevented him from contributing to decision-making for the last 15 years, and how he hopes to advance in the organisation's hierarchy to contribute to sustainability. "There is not a lot of focus on sustainability in the meat and dairy industry", Dehirm noted the sense of hopelessness is clear from his transcripts:

... I'll be honest, I've spent the last 15 years basically serving, maintaining red meat and dairy industries, which are not exactly known for their sustainability, and future thinking... I am trying to get enough experience to get a better position, you know, as a junior engineer, it's difficult to do a lot. But hopefully, once I've got a few more years under my belt and additional training, you know, maybe be in a position to change things, because what I see in those industries is typically the meat industry, there's not really a lot of focus on sustainability currently (EEE, Dehirm Cilnal, Phase 3, 2021).

Managers are unable to make decisions that promote sustainability since they are solely concerned with increasing productivity and decreasing costs. As a result there is a strong link between systemic thinking and future thinking, or, as Dehirm discusses, a link between management's short-sightedness and sustainability:

I think it's the management... Most of them try to work out how to get through the next day, let alone planning the next week, month, 30 years. There is a lot of very short-sighted thinking. And, you know, a lot of pressures to increasing the output and, push things to the limit (EEE, Dehirm Cilnal, Phase 3, 2021).

Based on the excerpts from Dehirm below, it is possible to infer that the industry's relationship with sustainability is one-sided in favour of the business. As the excerpt demonstrates, when it comes to constructing high voltage lines, the industry preferred a less environmentally friendly option rather than investing more money in improving the switch breaker on the high voltage distribution line:

... the transmission and distribution side... use sulfur hexafluoride as a collection medium, which, its global warming potential was insane. It's literally the most dangerous substance we know of. It's

only used in minute amounts. And in theory, it is completely contained within the structure. But leaks happen. These things are out, exposed... it's because, for high voltage, apparently, it's considered the only economical one, like what it's used for is that is an extremely powerful dielectric, which means basically, it stops arcs from happening, which... it is like the circuit breaker protection... So sulfur hexafluoride is very excellent at stopping that it from happening, which then means you can make much smaller, complex, space-efficient and cost-efficient switchgear (EEE, Dehirm Cilnal, Phase 3, 2021).

Dehirm's perspective on sustainability is similar to Jenniye's, who regarded it as a political campaign to keep the people pleased. Indeed, Dehirm believes that proposing sustainability as the future path is overly idealistic and that it is too early to see any significant change. Though a lot of effort and resources have been put into making the concept of sustainability popular, Dehirm and Jenniye believe that implementing sustainability in industry is too idealistic at this moment, as Dehirm says:

My impression is that it's either totally ignored, or you sort of get a token effort to produce some good press, saying, oh, look how green we are, you know, look at this green thing we're doing. Look at all that other stuff over there... (EEE, Dehirm Cilnal, Phase 3, 2021).

Among all disciplines, EEE were the least concerned with industrial sustainability. EEE have given up on all potential environmental problems associated with their profession. Instead, they held the designers and component manufacturers accountable. As a result, when any new electronic equipment was introduced, as Cody mentioned, the society focused on "making sure that it worked" as opposed to thinking about "the effect of all the waste produced by electronic products in the future".

... it feels like it's sort of relatively minor, like, you know, it's not as, you know, it's not as big as, you know, some other fields where, you know, you're radically altering, you know, the entire way you're doing things (EEE, Dehirm Cilnal, Phase 3, 2021).

Dehirm and Cody both explained how all of the components they use must comply with EU laws, which are trusted in industry to be as environmentally and sustainability friendly as possible. They hold that it is illegal for manufacturers to make environmentally hazardous products and materials. Therefore, concern about being environmentally friendly is completely unnecessary, as Cody expresses:

... I'm aware that we can minimise our environmental impact, but manufacturers are prohibited by law from selling circuit boards that include poisons like mercury or other heavy metals. It's also possible to check for things like RoHS, lead free... when you buy your components online. [Others laugh] As an electronic engineer, I haven't received much instruction on how to deal with the issues that the world faces and how to solve them (EEE, Cody, Phase 1, 2019).

Dehirm also addressed RoHS and verified his friends' remarks on the status of the EEE sector. He stated that there is little he can do to aid with environmental risks since most of the components have already been bought, but, in his opinion, the components are as safe as they can be owing to EU rules. He went on to say that other disciplines, such as component manufacture and design, might have a greater impact on EEE sustainability:

Pretty much like EU, I think, is probably made sure that you're using like the called RoHS components, which is essential, components that, you know, meet various environmental things, like, for example, they have to use lead-free solder... (EEE, Dehirm Cilnal, Phase 3, 2021).

According to Hugo, the sustainability movement is pointless in EEE, especially in New Zealand, as there is no way to fix anything. As Hugo, Dehirm, and Cody point out, they are not too concerned about where the parts come from. Unlike other disciplines where the lifecycle of materials matters, in their view, it is rather senseless to worry about this too much:

... I work in the industry, electronic and electric, and I think the only thing that we actually do that is sustainable, that's the fact we design our products to last ten years... The economy of fixing something is not there... And I don't think there are processes to

even fixing things... There is no process for that, especially in New Zealand... And lots of our equipment, we don't really care what and where it comes from as long as on the boxes it said toxic-free and safe. Like, if you can sell it into the EU, we don't give a shit what it is and who makes it. Is it ethical or anything! It just comes down to the price (EEE, Hugo, Phase 1, 2019).

Kairdra had observed the industry's unsustainable methods. As a result, when asked what she would do if she were in charge of decision-making to enhance the company's sustainability, she was positive that she would prioritise sustainability first, followed by other factors. *"I suppose I want to believe that I would prioritise sustainability first since that way, I would probably protect the company"*, she explained. As a result, when questioned why she would prioritise sustainability before anything else, she explained that it would be easier on her conscience and how it is ingrained in Kiwi culture:

I guess you can sleep at night... You know, it's a bit of a decision morally... It's a cultural thing as well (CHE, Kairdra Of Daevon, Phase 3, 2021).

Lannis offers a different view of industry, discussing her good experience working for a packaging firm whose primary focus was sustainability, as this is the primary public demand for sustainable packaging:

... I did my work placement last year when I was doing product design... Their advertising point was that they are sustainable designers... So that's like their selling point for people who want to develop products (ME, Lannis Krun, Phase 3, 2021).

One of the transcript's most surprising revelations is the pervasive influence of monetary considerations on choice. The perception that price was paramount was not limited to participants' personal lives; it extended to industry and how everything is determined by profit margins. Cody argued, for example, that the most significant obstacle to achieving sustainability is "greed". Both Akilah and Aragon elaborate on the concept of greed and describe how everything is being influenced by money. Money is the driving force for most of life's decisions, both personally and commercially, they argue, and sustainability can provide leverage to make it is easier to sell products.

... I believe it is more like designing your product for the project and then selling it, but I believe that, if sustainability engineering is included, it can have numerous advantages for your products (MP, Akilah, Phase 1, 2019).

... the only way you will cooperate, fully on board, because if they can make money from it... Money does the talking in the world and technology can make people a lot of money (ME, Aragon, Phase 1, 2019).

As Dehirm phrased it, "They are primarily concerned with profit". Dehirm expressed worry about the meat industry's lack of automation: "It is quite difficult to develop machines that are cost effective and capable of performing that function". His perspective on the meat industry's automation revolution began with a potential labour shortage caused by COVID-19, and he noted how the sector is attempting to avoid the next economic shock caused by a labour shortage. Finally, Lannis made another reference to profit in the industry, stating, "as a designer, you don't worry about sustainability; you care about profit".

So I think that their motivations are more in the case of probably not wanting to have economic shocks due to the fact that your workers are all sick. But there are also environmental implications, which are quite positive (EEE, Dehirm Cilnal, Phase 3, 2021).

Kaidra supported Dehirm's point about the industry and how it is only concerned about profit. According to Kaidra, the managers will usually consider the financial issue the top priority when it comes to decision-making:

... I just feel like the way they structure projects. So I guess, management, you know, they approve a certain project, but another project that could probably complement it, they won't get approved because of funding, like so then it's just a financial issue. But then it doesn't really help out the environmental sustainability side of things (CHE, Kaidra Of Daevon, Phase 3, 2021).

This section featured perspectives from a variety of disciplines. EEE's perspective on industry sustainability was bleak, and these participants couldn't relate to the environmental component of sustainability. The ME were similar. Participants who were working in the industry highlighted how none of them have

any power over decision making and, therefore, studying sustainability is futile. The only time a participant's work was substantially impacted by sustainability, particularly the environmental friendliness of their products, was when the firm was entirely focused on packaging, where sustainability is required in today's market. The emphasis switched to financial matters, with the business's profitability being the top priority.

4.3.2 Engineers' Perceptions of the Sustainability Paper

The "sustainability paper has been an exercise in frustration for reasons unconnected to the content", Jenniye argues, "I was so busy being irritated at how difficult it was to go through it". "If I could, I would have gone back and not done the paper", Cody commented, "and spent that money on a paper that actually taught me something useful". Similarly, as the expert below indicates, Kairdra is clearly seeking to express her dissatisfaction with the paper by comparing it to other familiar papers. A "talking paper", as she puts it, might refer to a collection of papers that encourage engineers to look beyond math and formulae and instead at the greater context. There are other papers that teach engineering students about subjects unrelated to their disciplines, which becomes "repetitive," as Kairdra states:

I guess sustainability paper is just one of those papers... as an engineer, I enjoy numbers and stuff that are definitive. But it was not always the case in this paper, I guess, because it's, look, like talking paper... I thought there are bits that were just repetitive (CHE, Kairdra Of Daevon, Phase 3, 2021).

According to Kairdra, the overall content of the paper was appropriate, but the paper itself appeared to be just another item on a list that the university had to offer just to say it had delivered such paper to students. She soon became demotivated because it appeared that no passion or motivation was taken to create the paper and, as Kairdra remarked, "why should I spend time studying?"

I guess overall the context was ok, but it was a bit vague sometimes, to be honest. It just felt like, the university used the paper to take a few things off the list. Like, they could say we were taught. If you know what I mean!... when you think like that, you would say,

if they don't really, like, put too much effort into it.... (CHE, Kairdra Of Daevon, Phase 3, 2021).

Yell mentioned that the paper is ineffective for an advanced year software engineering student and should be utilised instead as an introduction paper for students in the first year of university. He felt that the complexity of LCA and the paper design were incompatible with his discipline and would have wanted to complete a sustainability paper during his first year. As he notes in the following excerpt, there is an opportunity to enhance the paper:

I mean, in the current state, I don't think it's really useful for software. Maybe it is useful for people that are going into software, interdisciplinary projects, and other sorts of stuff. And it is sort of good to understand the environment, even as a software engineer. But going that deep into an LCA and the projects were mostly several related (SE, Yell Davurson, Phase 3, 2021).

One of the primary factors contributing to Yell's sense of exclusion was the LCA assignment. "No common characteristics", Yell stated, "I could not discover any points of connection between LCA and my discipline". Yell expands on this statement, as seen in the following excerpt, by emphasising how the LCA calculation was inappropriate for his discipline. He bemoaned the minute details required to finish his LCA assignment. Calculations are annoying, not because they are excessively lengthy, but because they are unrelated to Yell's engineering discipline:

I feel like it went a step too far. In terms of the calculations, usually for software students, like having to calculate how many litres of fuel some tractors use, and then how long does it take to wait for four mills to be used? What happens to the mills after the tractor is destroyed? Like, how much energy is used to make the tractor? That sort of stuff? I feel like it's excessive for software engineers. I have to do that sort of calculation (SE, Yell Davurson, Phase 3, 2021).

"I will not pursue a career in environmental engineering", Yell argued. Yell determined that the paper was unrelated because of its excessive emphasis on environmental laws and regulations, and the lack of flexibility in terms of incorporating other disciplines into the paper design. "It was environment based", Yell

criticised, "it was difficult to find a relationship with software." Yell further commented: "it was difficult to understand how this is going to help me for the long run". The only aspect that made sense to him in the paper was "risk analysis".

As seen in the following example, Osread and Raynard corroborated Yell's perspective. They also believed that LCA and other paper content were highly tied to the environment, and hence had no meaningful relation to software engineering. Raynard went on to say that the paper neglected SE algorithms and that, rather than employing system thinking to link software algorithms to environmental implications, the LCA assignment was more concerned with physical and direct connections between products and the environment. "The project we are working on now has less to do with software or cybersecurity", Meinrad noted, "than we like to admit."

... what is sustainability management when it comes to software? How does it really fit in? It is still on the level of vagueness... so it's kind of vague. The whole paper... rather than how the software itself helps by improving its use. So, it is very difficult to look at it, in our case, as software (SE, Osraed, Phase 1,2019).

That is hard to find out! Rather than saying something like an algorithm that could possibly be used to reduce environmental impacts, the project was not really about that; it was more about the physical side, which I guess made it not our area of expertise (SE, Raynard, Phase 1, 2019).

"I am convinced that the paper has nothing to do with my field of study", Yell said. As the following excerpt illustrates, Yell only recognised report writing as content that was relevant to his field. Report writing is not really a specialised talent for SE, but rather a generic competence for all engineering disciplines.

You can't really make it related to software, you know. And looking at numbers, things past, and the effects of them. The only relatable stuff was when, like in the report, when you're discussing how things can be done and different steps, that's where I was adding software attributes into the part of the autonomous system of the project (SE, Yell Davurson, Phase 3, 2021).

Hugo, Cody, and Sagar were unable to identify any concept within their discipline that was relevant. "It did not relate to our work", Cody stated, "it took our focus away". Sagar chose to "prioritise his electronics/mechatronic over it". Because, as he puts it: "it is much more important". "I will never use sustainability anyway", Cody stated, "I was waiting to see when I will be using it, but nothing". This demonstrates how distrustful participants have become as a result of the paper. Sagar, an [EEE](#) student stated that he had no interest in the paper as he preferred to focus on the specialist papers. When Sagar failed to see the connection between his field of study and the sustainability principles being taught, he shifted his attention to other subjects. Since the paper was not relevant to any [EEE](#) and [SE](#) disciplines, participants decided to ignore the lectures and not attend the classes. "I did not go to any lectures", Hugo said. Sagar also noted: "It was the same for me".

I felt like they were trying to cram a whole bunch into this one paper, and it did not really focus enough on anything for anyone to give a shit about it. I could have done a better job on the sustainability project, but I prioritise my electronics/mechatronics over it. Because it is much more important ([EEE, Sagar, Phase 1, 2019](#)).

Participants from [SE](#) gave further insight into why the sustainability paper was irrelevant to their fields. "The laws and regulations were irrelevant", Aldona declared, "most of them were about how you can use land and how you can use resources." Raynard shared this perception: "resource management is not relevant whatsoever and I am never going to remember these". "Not even going to think about it ever", Meinrad declared. By contrast, Aldona ([CE](#) participant) said "this paper actually was very useful". Her declarations outraged the rest of the room because [SE](#) participants were frustrated with how all the concepts they had to learn were unrelated to their discipline.

... Everything pretty much reflects back to my discipline, because everything you do as a civil, like when you are doing a structure, everything has to do with sustainability, so this entire paper I liked ([CE, Aldona, Phase 1, 2019](#)).

It is evident in this data how each discipline thinks and perceives things differently than the others. In a sense, [SE](#) participants who found cybersecurity lectures relevant to their fields felt alienated from rest of the content in the paper.

In response to Aldona's comment, the entire room went into an all-out frenzy. SE participants preferred to separate their discipline from others when it comes to learning sustainability and focus more on a specialised concept in their discipline.

I think it will be tough to find a general example that everyone will be able to relate. I believe it needs to be split off and be more specific toward disciplines (SE, Raynard, Phase 1, 2019).

It can be branched, actually. There are some things that are general, and you can teach to everyone like risk and resilience and that stuff, and some of the case studies are quite interesting just to see the effect of those things, and then you should split them off and go into more specific points of sustainability for the disciplines (SE, Tancred, Phase 1, 2019).

Aldona of course did not agree with their point of view as she was already familiar with what the paper is trying to teach her. As discussed previously, in the argument between them about the cybersecurity lecture and how she was not pleased about that, she also pointed out that, instead of covering a lot of lectures with guest lectures to please everyone, it would be preferable to focus on one topic, whether software related or not; she believed this would benefit everyone.

Not on the civil sides. There is no need to improve it. But I like to keep it as one class instead of splitting off and using more resources. Instead of having one cybersecurity lecture, which was not really software, it was cybersecurity, so instead of having more variety of lectures, just focus on one thing. Let's say software so that we all can learn about different knowledge. I think it is important we all familiarise ourselves with all the other disciplines. So, if software learns about all other disciplines, other disciplines need to learn about the software. It is important because everything will be digitised in today's age to bring more software-related lectures. So, something like: one civil, structure, electronics, mechanical, software, etc. (CE, Aldona, Phase 1, 2019).

Raynard first disagreed with Aldona, stating that there would be issues with consistency and background material for the other disciplines in the class. He emphasised that, similar to software engineering students, civil engineering students would face the same fate if they began learning about discipline-bounded ideas in SE. “There will be some lectures where civil engineers will have no idea what is being introduced”, Raynard added.

The problem with that, is that there is a lot of background knowledge that is already needed to go onto it. We can talk about encoding systems and how they need to be sustainable and unbreakable and that kind of stuff. So, there is a lot of stuff that you kind of need to know before you are going to it. Which is why I think breaking off would be better (SE, Raynard, Phase 1, 2019).

Aldona proposed that they “should just keep the paper basic”, and Raynard emphasised “what is the point of anyone taking the paper?” Aldona and Raynard both make valid arguments concerning whether or not to incorporate discipline-bound topics into the paper as a whole. The intriguing part of their argument is that the difference in perspective is once again immediately noticeable. SE participants who have been forced to learn concepts unrelated to their disciplines understand how a CE would feel if they were forced to learn about software sustainability. The sense of displeasure was not specific to students only. Without even being questioned, Pyrrhus’ opinion of the sustainability paper was poor. According to the following excerpt, Pyrrhus claimed that the sustainability paper was taught by CE for CE. He further commented that certain disciplines have more connection with each other than others. For example, EEE has more in common with SE than it does with CE.

... I think most of our [redacted] papers have been designed by a small subset of engineers that are dominant currently. And they see everything from their own perspective. And they think that everything is civil. But not everything is civil. And the umbrella of an engineer is really a constructed concept, like an electrical or mechatronics engineer, who is actually much closer to computer science. And computer science is much closer to them than they are to civil engineering. But what you’re looking for here is this compartmentalization (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus' main worry with the common papers taught across the engineering school, which were intended to cover sustainability for all disciplines, was more about the topics/concepts. In his opinion, teaching what was being offered in those papers to software engineers was "utterly useless". Pyrrhus highlights a few issues with the present state of engineering education, noting that many institutes seek to operate on the assumption that papers from other fields may be shared. Pyrrhus argues that teaching engineering to students from a wide viewpoint is dishonest and inaccurate, since each discipline has its own distinct way of seeing things. In some ways, he is highlighting what Raynard and the other [SE](#) participants were attempting to communicate by separating their discipline from sustainability education. They all want to have a independent paper on software sustainability:

And this is the main problem that I think education in engineering really needs to work on. There is this fundamentally wrong idea that is being pushed by people who just want to collapse education and something that it's, you know, one size fits all... like the first two years. And this completely misses the point... we're viewing things from such different angles... But that doesn't work, like, this is, like, even I personally think first-year is not possible to be shared... people can find tricks around it, they can find ways to justify it but... students enter engineering and how little they learn while they're doing engineering... Oh, everybody has to be told the same thing! Everybody should do CO₂emissions... it's abysmal ([SE, Pyrrhus, Phase 3, 2021](#)).

As Pyrrhus argues, it is not fair to students to concentrate on a concept that is irrelevant to them, and each discipline should focus on what is important in their degree. In the following excerpt, he discusses what different disciplines could focus on if they want to learn about sustainability:

But this is a fail for a software engineer, like a software engineer needs to tackle the things that I told you, and an electrical engineer needs to tackle, okay, what are the redundancies that I'm going to have, such that I minimize the chance of having to turn on the coal generator, right? A civil engineer will have to tell you, this is the best way to build it more efficiently so that it's structurally safe because it's going to be on the South Island. And there are lots

of earthquakes there. So obviously, there's no sustainability of the whole thing getting destroyed, and I have to build it again, like, plus, maybe they can come up with smart ways to maximize cooling, because oh, you know, we're going to build it on a cliff. And there's going to be lots of draught coming from a cliff, or we're going to put it all the way underground, there's going to be permafrost, like, these are all civil concerns. This, but these are not software concerns. So each of the fields needs to be given an answer on their own, and then perhaps collectively, they can have a summary. But if a student from software fails to identify and discuss these things, then they fail. It's as simple as this for me ([SE, Pyrrhus, Phase 3, 2021](#)).

The approach that works best to rectify the issue with the sustainability paper, according to Pyrrhus is "a total redesign of these papers" with all disciplines "to contribute material and also teaching". Pyrrhus elaborates on this in the following excerpt, and introduces a new challenge: the fundamental difficulty with co-designing and reorganising the paper, which relates back to how each institution handles their finances. As soon as one school becomes in command of a paper they assume full control over it and won't let other parties to contribute. This situation destroys any sense of communal work, and undermines the capacity of different areas to provide their input. As Pyrrhus advises, considering the economic aspect is necessary before trying to rearrange the paper. In the end, as Pyrrhus points out, an equal contribution from each discipline to the paper would make more sense:

... So these need to be shared papers, which means that the structure of the papers is the way that their economics need to change because the problem here is really economics. Like you have, we have two schools, that are three schools that are fighting for x, you know, probably know what's going on, which means that, oh, the moment one school grabs a paper, they're like, it's ours. Now we're going to do whatever we want. We don't care. And we ensure we take all the efforts, and there's no input from anyone else. This is the situation and the, like, I think it's, it's a result of how the system here is designed like at the university, and I don't know, to other places that have this kind of system, like instead, I think,

would have needed for papers that are shared to be taught together, and then come up with an economical solution to justify the schools, or not use the school as a means, as funding, as a cost centre, we have divisions like we have, the HECS division is essentially the STEM division of the university. So there should be other ways. Yeah, like there shouldn't be a single unit managing this thing somehow, or if there's not a single unit, then there should be some sort of weighted average, or a weighted split of the efforts accordingly, such that everybody contributes. So software engineering would need to contribute material, like two weeks, for example, at least on each of these papers. They cannot be 12 weeks on civil; otherwise, they're useless to us (SE, Pyrrhus, Phase 3, 2021).

Additionally, Pyrrhus explained how "there is not enough space" to include papers that teach students general knowledge. Especially if it is not discipline-specific, i.e. teaching environmental engineering in software engineering. In the following passages, Pyrrhus explains how software engineers have to learn about the technical aspects of software engineering before graduating. Therefore, there is not enough time to cover sustainability again if it is already being offered:

... So if we are to offer something on sustainability that's already offered, double-dip it. That means that we'll have to take two slots. We don't have the space to do this. Because our software engineers, they need to learn software engineering design; they need to learn databases; they need to learn computer systems; there's a bunch of technical and design-oriented things that they need to learn... So what we need is co-teaching and co-design of sustainability papers. Instead, what has happened is certain people have taken over these papers, and they run them the way that they thought it makes sense for them... papers that are shared among the degrees are, by, many people in the computer science department, view them as unnecessary baggage. That is the reason for someone to not do software engineering... it's viewed as a waste of time (SE, Pyrrhus, Phase 3, 2021).

The reasoning as explained in the above extracts goes back to the problem with engineering education and how there are no available places to offer specialised courses. Especially if there are already several courses that are meant to cover a topic. The software and computer science school need to focus on the main subjects that any graduate software engineer needs to know. The technically heavy subjects are designed to help a software graduate to compete with other graduates. Pyrrhus' discussion of certain disciplines being more connected than others is also visible elsewhere in the data: one [EEE](#) participant, for example, also pointed out that the paper was not relevant to them, as it tried to focus more on environmental aspects. According to Hugo, the best way to make a discipline more relevant to sustainability would be to emphasise its technical aspects:

... what we had to do was write some waffle about the environment. It was not like you really had to do a lot of research and get the real technical skills, like you are going to actually design the facility or actually design a car with sustainable things in mind. It got some vague information... For example, for the battery thing, it was all like we are going to do batteries and here is the impact, and this is what you need to consider... I don't think the paper was able to merge technical skills of any discipline, especially EEE, with the concept being taught ([EEE, Hugo, Phase 1, 2019](#)).

4.3.3 Engineers' Perceptions of the Sustainability Concept

The concept of sustainability is understood in a variety of ways by each discipline in this study. Sustainability is defined in a manner that is unique to each participant, which is based on their individual experiences in their own discipline. "From my perspective, sustainability should be the way that one, particularly an engineer, tries to save the environment as quickly as possible", Malchom added, "it's a fairly large scale". Condon's and Malchom's notions of sustainability are primarily concerned with the environment and resource conservation. Nyaja's and Ravyn's were more concerned with recycling and material management.

I think more like how do you relocate resources for use in the future to reduce pollution ([CE, Condan, Phase 1, 2019](#)).

I like to add that sustainability focuses more on the environment... Damaging the environment is bad since everything is dependent on it. So as long as the environment is here, it is an important thing for us to sustain it (MP, Thaddeus, Phase 1, 2019).

Engineering is like a recycling process is. We should try to be friendly to the environment, and we will benefit from the sustainable engineering and for the human being for whatever other animals, plants... (MPE, Nyaja, Phase 1, 2019).

I think the key point as we engineers should make sure that the resources should be enough for our future generations (MPE, Ravyn, Phase 1, 2019).

The vast majority of disciplines looked back on their discipline-specific papers and contrasted how their role as a sustainable engineer matched up with what they had been taught. As was shown above, the fields of MPE and CE focus the most on environmental impact through their use of recovered and re-purposed materials. Malchom adds his personal opinions by saying:

Sustainability, in my opinion, should be a means for everyone, especially engineers, to attempt to save the environment as quickly as possible... Because I've been studying civil engineering, where we create roads, highways, and bridges, I believe it's sustainable for us to think about recycling and reusing natural resources like sand and concrete (CE, Malchom, Phase 1, 2019), and how to extend its useful life as well as to make the most of it (CE, Condan, Phase 1, 2019).

MPE participants all agreed with Malchom and Condan. Aldona backed up her peers' statements by emphasising the importance of environment in the CE discipline. Her perception of sustainability was mainly to save the environment and reserve as much material for the next generation as possible.

We have to figure out which will be the best materials to use in the first place and actually find out how to do the mitigation approaches, find out the location you are working at will be least harmful to the environment that it would be to do it on natural reserve or something... (CE, Aldona, Phase 1, 2019).

Jenniye emphasised the significance of resource management. Her definition of a sustainable system is one in which inputs and outputs are balanced and waste is kept to a minimum.

It was literally the definition that we need to have a sustainable system where the use of resources does not occur at a greater rate than those resources can be renewed. So, it wasn't even necessarily just relating to renewable energy. It was just, it was effectively almost a mess in and mess out of resources, if you like (FE, Jenniye Orso, Phase 3, 2021).

While Jenniye emphasised the significance of resource management, she also emphasised the relevance of design and requirement engineering. As a FE, Jenniye explained how her design and material choices might literally be the difference between life and death, and she was able to perceive sustainability in her career through that lens, as seen in the passage below:

... the concept of sustainability is going to mean that fire-rated and fire-resistant products are going to need to be developed from sustainable and renewable resources at some point. And they will, at some stage, and this is happening already. At some stage, the focus will shift from things being fire-safe to being fire-safe and sustainable. And then, there will be continual product development requirements with sustainability as an increasing consideration (FE, Jenniye Orso, Phase 3, 2021).

Naturally, with that stated, she said, "If I'm going to be an engineer, I'm going to have to think beyond the box. And I need to consider the broader context of the project I'm currently working on, as well as how we connect it to the rest of the world". Kaidra's perception of sustainability in her profession paralleled that of Dehirm and Jenniye. In certain ways, her comprehension is entwined with discipline-specific notions and system thinking. Kaidra also emphasised the value of strong design and requirements engineering in her discipline-specific tasks, as seen in the paragraph below:

I guess, like designing products or processes. Yeah, they're products and processes that are environmentally friendly, and they use renewable products. So I guess that's the first thing that comes to my mind... I don't know about the dairy processing plant. I guess,

like, making sure that you restrict water use or reuse, recycle water use more often and then integrate energy. So, like, integrating your heat and stuff. And then I guess the products that you use are human, just the chemicals for cleaning, just making sure that they're biodegradable and not toxic and stuff like that (CHE, Kairdra Of Daevon, Phase 3, 2021).

Kairdra was aware of the importance of incorporating sustainability. Additionally, she recognised that sustainability is not a quick remedy and needed patience. Notably, she was also able to connect sustainability and time, as demonstrated by the following excerpt:

Like, something that can be obviously sustained for a long period. I guess a solution that is obviously going to, like, in itself has been able to, you know, obviously, sustain itself for years, you know, like, isn't just something that's an immediate fix I guess (CHE, Kairdra Of Daevon, Phase 3, 2021).

Participants in EEE defined sustainability in terms of design and development, with an emphasis on the environment. The environment isn't really a primary concern, though; rather, it's more of an afterthought. Furthermore, critical technical requirements that must be addressed prior to the start of any project were mentioned, as in Hugo's comment:

Some of the most sustainable electronic design you can do is just by making it better in terms of design... if we are going to be sustainable, we need to start developing a better design. That is where engineers could focus. We are capable of developing new solutions that could help with environmental issues and help the future generation... but learning about the environment as an engineer isn't a huge financial gain for us; it's more like a consideration that we must make among many others... (EEE, Hugo, Phase 1, 2019).

Sagar "agrees with that". Interestingly, Aragon also backed up this comment by stating that CE, more than others disciplines, must consider sustainability. He also provided an example of what sustainability means in his discipline of engineering, which has more to do with technology and better design than it does with the environment.

I would definitely say certain disciplines need to consider it MORE, such as civil, for example, when they are building a road or a structure because they need to pay close attention to environmental issues. And as for myself, a mechanical, I would say more about materials. What materials my design is using? What are they made from? But then also considering if I am designing a car, a classic example, if I am designing a car, will it be able to use that technology indefinitely. So, I think it is more to do with technology and the materials that it is made of (ME, Aragon, Phase 1, 2019).

An interesting find for EEE participants was the talk of electrostatic discharge and how it is one of the most fundamental design aspects. Furthermore, they mentioned how safety, and manufacturing a robust and reliable component, is much more important than environmental studies.

... To be sure, perhaps the EEE side of sustainable engineering can teach students how to design devices that are more resistant to electrostatic discharge (ESD) and similar hazards. Teach some concrete examples of ESD and how it applies in industry... (EEE, Hugo, Phase 1, 2019).

oh robustness and safety (EEE, Cody, Phase 1, 2019).

yeah, how to fit in the industry. Like IC makers do it all the time. But you know, for example, in the electronic class number of things were blown up in there for stupid things that actually should be protected (EEE, Hugo, Phase 1, 2019).

no one taught me how to start putting diodes for my power and boom (explosion)... (EEE, Cody, Phase 1, 2019).

That is some of the simplest electronics design you can make that makes things a hell of more sustainable just by making it improved in design (EEE, Hugo, Phase 1, 2019).

"It's ensuring that the systems were created in such a way that everything we do can continue to operate", Dehirm added. "Of course, environment is a component of it", he said, "certainly one of the most difficult ones to apply directly". Further examination of his transcript revealed that the majority of aspects given

in the discipline-bound theme are what Dehirm feels are relevant to his discipline. The components of design and automation stand out the most. Dehirm described how sustainability is not a primary issue and is considered as an afterthought in society. He was concerned that it could already be too late to preserve the environment and humanity. Billions of dollars are being spent to correct the problems already in existence, but it's incremental and not as practical.

That's really in the name; it means that if something's not sustainable, if you keep doing it one way or another, it is, something's going to give, that's going to break. We often seem to think it's a nice thing to do. But it's, you know, tends to be sort of the second or third or fourth priority, whereas, in our society, it's really getting to a point where, you know, some of these, we're going to be hitting critical points very soon if we already haven't ([EEE, Dehirm Cilnal, Phase 3, 2021](#)).

Interestingly, Lannis also included design aspects when she was explaining sustainability in her discipline. She expressed that in the current state of the world, it does not matter whether you believe in sustainability or not: the driving force will be profit anyway. The public, according to Lannis, has greater power to control the market and force the engineer to design sustainable products:

The thing with a design... There's no point in designing something no one will use, you know, and if you look at the public perspective now, as we need to be more sustainable... it's like your problem is that people won't buy your product. Even if you don't learn about sustainability, your driving force needs to be that people won't buy your product if it's going to be detrimental to the planet or the environment. So, like, you can look at it from multiple aspects, like you yourself, as a designer, want to be sustainable. And then that would be useful. Or you, as a designer, don't care about sustainability, but you care about profit, but you won't get profit if you're not sustainable ([ME, Lannis Krun, Phase 3, 2021](#)).

[SE](#) participants' perceptions of sustainability in their discipline were different from the rest, but not so different as to be unrecognisable. When asked how they perceived sustainability in their field, [SE](#) participants provided a range of responses. They did not consider that sustainability was as critical to them as

it is to other disciplines. They had a hard time connecting with the sustainability paper/concept. "What exactly does software sustainability entail? Just where does it belong, exactly? To this day, it remains on the level of vagueness", Osraed commented. Raynard followed this up by saying, "that is hard to find out!" As the following excerpt illustrates, Meinrad did not believe that sustainability plays as big a part as it does for the rest of the disciplines. Meinrad further hinted that software sustainability always relates back to the project and design and not the software:

... software is going to come down to the sustainability of the project that we are working on, not so much as for actual software. Maybe the redundancy and stuff like that, definitely it is part of it, but I don't think it is as big of a factor for us as it is for other disciplines (SE, Meinrad, Phase 1, 2019).

Meinrad was unable to connect sustainability and software. Still, Raynard corrected him by emphasising how software engineers have a greater impact on sustainable practice. He reminded them all that being precise and paying attention to details is far more critical in the software engineering discipline, as demonstrated by the following example:

I would say it is being more precise when you are actually automating something. Because if you are using, let's say you are using maybe 1 kg more carbon and you are doing it 10000 times that are much more carbon emission than doing it once as a civil engineer (SE, Raynard, Phase 1, 2019).

Osread corroborates Raynard's claim by stating that SE does not operate alone, and other projects are dependent on SE products and codes:

Yeah, I think we are trying to say that software does not exist in isolation with anything else. It helps to work better and improve, you know to actually enhance it, rather than just sit by itself, so it really needs to be linked to something else to see how it can improve other areas (SE, Osread, Phase 1, 2019).

Yell also supports Osread's and Raynard's statements, expanding on the idea of fine calculation and the need to be precise when it comes to software engineering, as it can help with reducing energy use and in turn lower carbon dioxide:

I guess that's one way of being sustainable in terms of software, like, you have to be able to deal with the cost of using that computing power and the effects of how much energy is used. And then the benefit of your software, as you know, despite the negative effects of the electricity we can use (SE, Yell Davurson, Phase 3, 2021).

Yell described his project and addressed how forestry is unsustainable. However, an analysis of his statements reveals that the unsustainable components do not pertain to environmental concerns, but rather to the industry's failings in terms of worker accidents and energy use. Yell's sustainable forestry model is based on automation. He mentions that the use of computers and robotics in the industry would eliminate many dangerous injuries for forestry workers.

Yeah, we found problems in current forest harvesting! ... injuries, just a bunch of different energy problems, processing. And using autonomous forest harvesting, where there are no people needed for physical labour, the machines just do all the work. You can eliminate problems. So, you see, it's making this whole system more sustainable. And if you use electric vehicles and stuff like that, you can make them more sustainable because of clean energy. So those are things that can build up to be more sustainable (SE, Yell Davurson, Phase 3, 2021).

Raynard was not pleased with a single example and continued to emphasise the importance of efficiency in terms of software sustainability. Raynard's excerpt, followed by Meinard's comments below, relate to software requirement engineering, a field in which basic project management and an understanding of how good software should be created are critical:

When you talk about efficiency in other disciplines, for example, you are building a car as a mechanical engineer, your efficiency is how much fuel usage you're getting per mile or whatever, but when you say, 'Can you analyse this program and its efficiency?' you are going to talk about memory usage, and clarity of code, and all of this stuff is not really relevant to the environment in any such way. So, it is kind of hard because none of our previous papers talked

about carbon emission and not so much electricity usage either (SE, Raynard, Phase 1, 2019).

I did a paper on software methodology in the first year. It was the first year that was running, and it is probably more along the sustainability line for software than this paper could probably ever be. So, it is better to keep it the same. They went through testing methodology, format, and documents you have to write and how to set them up nicely and everything (SE, Meinrad, Phase 1, 2019).

Meinard's directing attention to a certain paper taught at the university was rather interesting, as was his friends' agreement with the statement. Meinard goes even further, stating that "you could certainly squeeze the sustainability concept into that paper". Since everyone else did that paper, they all agreed with their friend's comment. Yell also mentioned the same paper, focusing on the technical aspects of developing a software rather than environmental engineering:

I think of Pyrrhus' paper, the software engineering methodology, but he's changed the name now. But that just goes through the process, the proper process of developing software, the requirements specification, and different documents and steps until you reach the point where you can actually develop software. That sort of thing is a life cycle of software. And that's making you think about all these different things before you start developing (SE, Yell Davurson, Phase 3, 2021).

Pyrrhus' paper, named "Advanced Software Methodology", was selected as the best paper akin to sustainability by all SE participants. Pyrrhus described the paper as follows:

... we're going through the whole lifecycle of software engineering; it might be that we were inadvertently covering some of these things... So on many occasions, I'm telling them, look, you know, if you want to make money, you know, you have to be efficient in your processes. So you shouldn't you should be reusing code; you shouldn't be implementing it from scratch... if you do proper testing, which means that you're doing enough, but you don't do too much, then it normally connects almost linearly with time, at the

design level... we have a software engineering design, which are the process to make software. And then, in order to make the software more efficient, I think we did discuss a bit about ways to adapt, load such that you don't do over-provisioning... the topics that we discussed was around auto-scaling. Auto scaling is the capacity to add or remove computing resources based on the load that you have (SE, Pyrrhus, Phase 3, 2021).

The paper covers a broad range of topics, especially in the domain of software engineering. However, after reading the excerpt, a few themes emerge that catch the reader's attention. For example: the life cycle of software engineering; making money; efficiency; reusing codes; design; provisioning; scaling; and optimal management of computer resources. Pyrrhus' example below demonstrates the paper's primary goal more clearly. The primary goal is to reduce waste and make the system, in this case the data centre, run more efficiently. In other words, the emphasis is on minimising waste while simultaneously ensuring that redundancy can be managed.

So, for example, if everybody watches Netflix, Netflix needs to provision more machines to satisfy people. So an approach that you could have is, what is the maximum ever that I'm going to need? A million machines. Okay, have a million machines running all the time: this is not sustainable. So what we'll discuss, for example, is, in auto-scaling, is that you try to figure out and adapt on an automatic, automatically, and turn on and off machines based on the necessities that your system has. And this is quite a bit around my research area as well. So it's the effective management of computing resources. So I guess there are a variety of avenues that they might have said something like that (SE, Pyrrhus, Phase 3, 2021).

At first glance, it appears as though these concepts have nothing to do with sustainability, and that was my initial impression as well. However, as Pyrrhus explained, these concepts are explained in order to meet sustainability requirements. He then delves deeper into software requirements, as illustrated in the following excerpt:

Yes, but one of the requirements that we need to be meeting is sustainability. So another thing, so I, first, one of the first things

that I tell them in the first two weeks is the split between functional and non-functional requirements. Functional requirements are what the software needs to be doing. Non-functional requirements are constraints under which software needs to be operating under, and how different is it: the system needs to be secure, or the system needs to perform fast with, the system needs to be sustainable, or the system needs to be burning a maximum of that amount of emissions, or the system needs to be carbon-neutral. Like, this is an input, and this is a requirement that I need to meet when I'm doing software design. So yes, I think there is a component that is specific to yes to software engineering, okay. There's definitely a component to that (SE, Pyrrhus, Phase 3, 2021).

As seen in the following excerpt, Pyrrhus' broad argument for sustainability in general has two overarching meanings. The first is primarily concerned with "future thinking". The second definition, on the other hand, reflects the importance of environment in ensuring the contentious operation of systems.

Sustainability in general! I would say it has two meanings. So it's the capacity to be able to continue doing things in a way that things will continue to operate, and they will not collapse. And I think this is the general master definition. Then, based on that, we're moving on to environmental sustainability, which I think, by default, nowadays, starts to mean, that our processes need to be able to continue to operate, such that we do not destroy the environment or that we do not interfere with the process of the environment to the extent that they will fire back at us and mess up our own processes (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus argues that, in relation to software engineering, sustainability "has three separate components to examine, depending on your perspective". The first component is concerned with the domain being omitted from the equation. Concentrating exclusively on the end product that software developers must create is, in some ways, inefficient. Software engineers, in certain sense, are not restricted to small, specialised areas; they can work in any industry. Pyrrhus cited an example involving the creation of a new app to aid in the resolution of environmental issues.

... we should remove the component of the domain... software engineers could be working for the city council, and they might ask us to create a software for them that will tell them what is ideal number of cars that we should have on the streets... Now, the domain of this is probably something like civil engineering or, you know, transportation engineering. But you need software to do this. So, this is something that software engineering can assist with, but it's not really central to how software is engineered... (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus added a number of further points. While examining the sustainability of software engineering, it is prudent to assess both "execution" and "development". In some respects, software execution has a more obvious impact, because the impact is also easier to quantify. As a result, if more power is required to execute the programme by heavy-duty components, more energy is consumed. Additionally, a closer analysis reveals the intelligent design and algorithm.

Software engineering itself, I think there are two components to it. One is sustainability in the execution of software itself, which means that the software when it runs when it operates shouldn't be burning too much CO₂. It's essentially like you need to minimize emissions when the software is running, and this very much connects to how many computers you have running... sometimes, you know, you might be pushing them a little bit harder. And this causes them to kind of run faster, so they start consuming more power and more energy (SE, Pyrrhus, Phase 3, 2021).

As for the development phase, as the name suggests, it is the process where the software or product is being made. As with any other product, to develop an app or software, it must be developed first.

And then the other part has to do with the development processes around software, I would say. So this is what leads to software being made (SE, Pyrrhus, Phase 3, 2021).

Pyrrhus argued that social implications are enormous for software students, and are sometimes overlooked because the person responsible for teaching the paper is not entirely aware of them, just as they are (SE) not fully aware of social

implications for civil or chemical engineers. Finally, Pyrrhus developed his previous discussion of the potential to redesign and co-design sustainability papers throughout engineering education.

So I'm from a software engineering perspective, there's like the impact that software has on society is tremendous. You see what's going on with social media, right? So it's, like you have certain, like people like Trump being elected, or people like Boris Johnson dragging the UK out of the EU by manipulative usage of social media and in the end software, and what are we how, who is going to save this? They don't see this. Because if they don't even think they know, their social implications in software engineering, because they don't know software engineering. In the same way that I wouldn't know civil or chemical engineering. That's why we need to consensus, and even better, you need to co-design, and you need to say, look, you each of you, you have two or three weeks to teach, and you teach for two weeks, and then we do some sort of split-up of the economics of it, because remember that economics is the primary driver here. So if you want to find a solution, you have to find an economically viable or economically sustainable solution, to use the term. Don't forget the economics. This is what drives everything ([SE, Pyrrhus, Phase 3, 2021](#)).

4.4 Quantitative Results

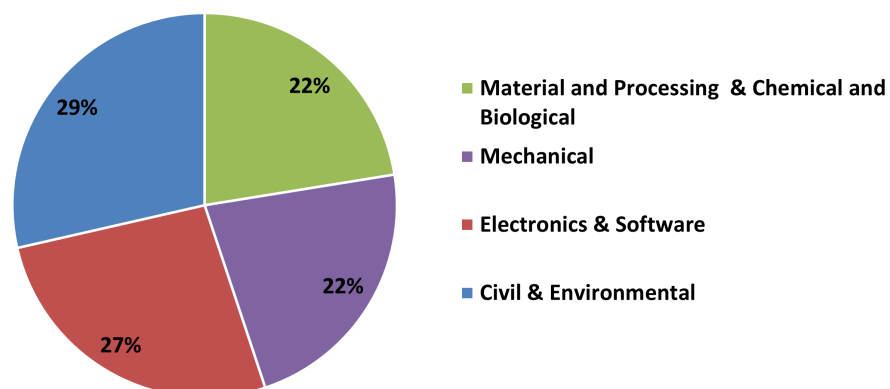
This section presents the findings from a questionnaire conducted to investigate the research question. The questionnaire was designed to gather data from a sample of engineering students enrolled in a sustainability paper. The data was analysed using statistical methods, and the findings are discussed in relation to the research question. The results provide valuable insights into the topic of study and contribute to the understanding of the phenomenon under investigation. Overall, the quantitative results section provides a comprehensive understanding of the questionnaire findings and the implications of the research for practice and for future studies.

4.4.1 Background of Respondents

This section discusses the respondents' disciplines and the rationale for categorising them into four groups rather than into all eight disciplines. The entire number of participants and the final group to which they were assigned are depicted in Figure 4.2. Figure 4.3 and Figure 4.4 illustrate the rationale for grouping the respondents into distinct fields.

Figure 4.2

The breakdown of respondents by discipline - percentage of respondents classified in each similar disciplinary group



Distribution of Respondents by Discipline

Figure 4.2 summarises the number of students who completed the questionnaire and the representative sample utilised to present the data in this work. The real percentage of respondents before being presented in their discipline groups are as follows. Chemical (4.1%), civil (24.5%), electronics (16%), mechanical (2%), environmental (4.1%), material and processing (18.4%), mechanical (22.4%), and software (8.4%) engineering disciplines were represented in the questionnaire. These disciplines were combined to make the discussion more consistent and the data visualisation more understandable, as there were a few disciplines with insufficient participants. To that purpose, the eight disciplines' responses to the screening question were thoroughly analysed, and it was determined that grouping them according to their paper project was the optimum approach.

The screening question to group different disciplines into distinct categories was chosen based on their choice of paper project. Students were required to submit a comprehensive LCA of a real-world scenario. They were given the freedom to choose their own project and team for the paper. Students were asked to inform the researcher as to which project they have taken. The top projects depicted in Figure 4.3 illustrate the rationale for putting certain disciplines together. Chemical and material processing disciplines, as well as civil and environmental, electrical and electronic, and software professionals, all collaborate on a few projects (see Figure 4.4). The only exception from Figure 4.4 is the Electric Vehicle in Australia and New Zealand topic, which was favoured by every engineering discipline. When it came to categorising participants by discipline, any project with fewer than five students was eliminated, and only the largest groups were taken into consideration.

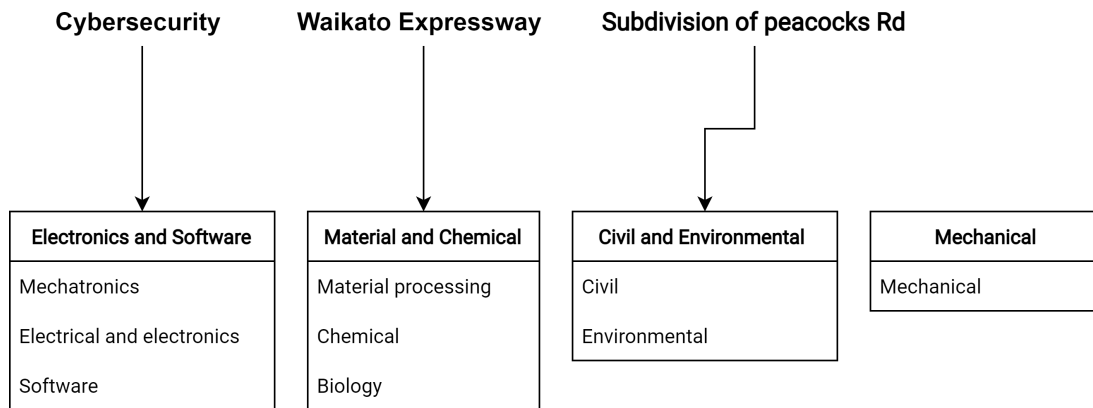
Distribution of Respondents by Project

Table 4.1 offers a list of all the topics students could select from for their projects. Out of 14 projects, Electric vehicles in Australia and New Zealand had the greatest percentage of students undertaking the project, with 26.53% (26/98), followed by Subdivision of Peacockes Road and Waikato Expressway, with 14.29% (14) and 13.27% (13) respectively. In addition, 7.14% (7) of students were part

Figure 4.3

Group selection process and the project that made them into their groups

Group Selection Based on the Screening Question



of both the Cybersecurity and Establishing a Cycle/Scooter Network in Hamilton projects. The largest percentage of projects with more than 5 student team members is shown in Figure 4.4; as mentioned, these projects were utilised to group disciplines with shared projects together.

Figure 4.4

Top selected LCA projects based on respondents' discipline

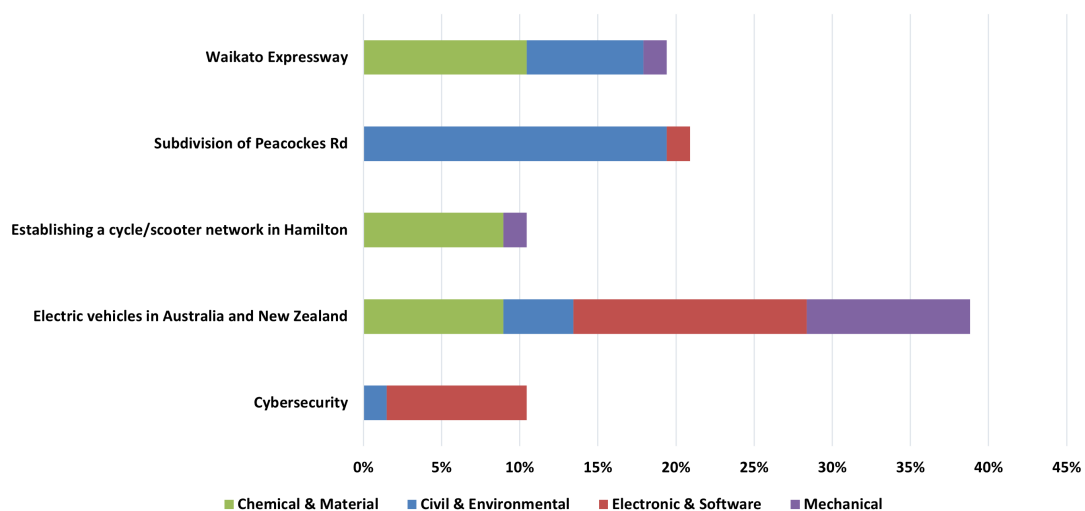


Table 4.1

Full LCA projects list and the total number of respondents for all projects

Projects in the paper	Frequency	Percent
Hydrogen Cars for Hamilton	1	1.02
Robotics in Agriculture and Forestry Industries	2	2.04
Mars Curiosity Rover	2	2.04
Upgrade of the Hamilton Wastewater Treatment Plant	3	3.06
Ruakura Land Port	4	4.08
Pumped Storage for Large-Scale Electricity Storage	4	4.08
Huntly Power Station Upgrade	5	5.10
Batteries for Domestic, Industrial and Large-Scale Storage	5	5.10
2011 Tōhoku Earthquake and Tsunami	5	5.10
Cybersecurity	7	7.14
Establishing a Cycle/Scooter Network in Hamilton	7	7.14
Waikato Expressway	13	13.27
Subdivision of Peacockes Rd	14	14.29
Electric Vehicles in Australia and New Zealand	26	26.53
Total	98	100.00

4.4.2 Participants' Perceptions of Sustainability

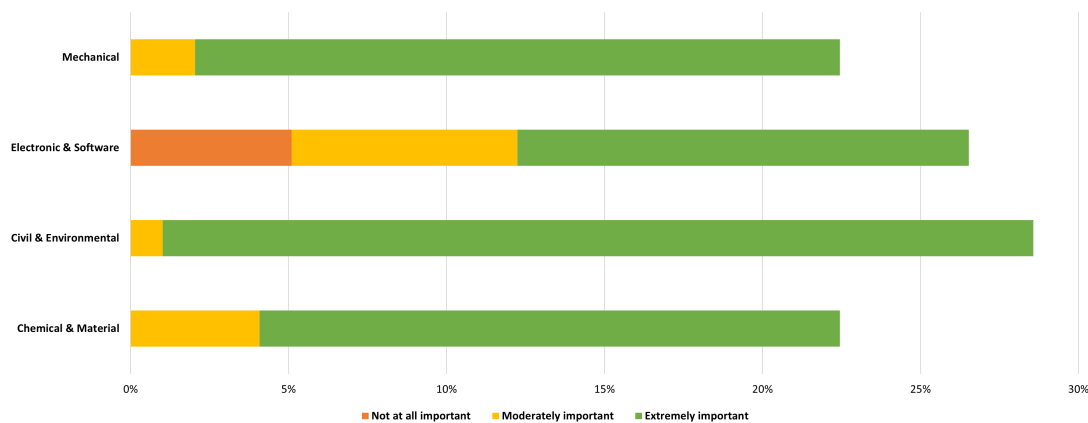
Because the perception of students when it comes to sustainability was vital to the study, the questionnaire 6.6 featured various questions to create data on different disciplines' perceptions of both sustainability in general, and sustainability with specific reference to their disciplines. Respondents were asked to express their views on numerous critical components of sustainability and the sustainability paper they were taking. This sub-section summarises findings from analysing data relating to different engineering disciplines' attitudes towards sustainability.

When participants were asked whether sustainability was important in their field of study, the vast majority of them stated that it was highly important (see Figure 4.5). For civil and environmental engineers, 28% ranked sustainability as extremely essential in their profession, making them the discipline to place the highest value on sustainability. Sustainability is essential to mechanical engineers, just as it is to civil and environmental engineers, with 20% of them deeming it extremely important. Following mechanical engineering, 18% of chemical and material sciences disciplines rated sustainability as extremely important.

The only disciplines that were hesitant and did not place a high priority on sustainability were electronic and software engineers. Around half of electronic and software engineers (12%) were unsure whether sustainability was a priority in their discipline.

Figure 4.5

Respondents' perceptions of the value of sustainability in their discipline

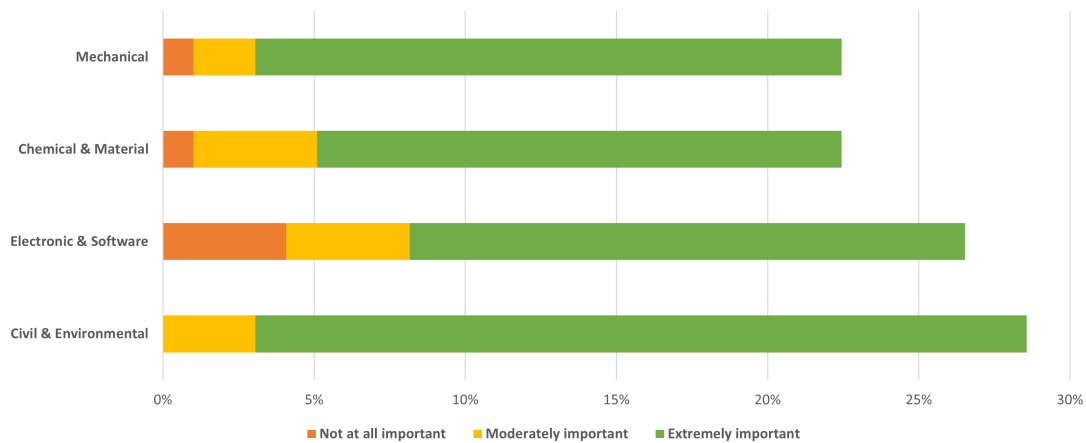


Respondents were also asked to indicate how they personally perceive sustainability. Comparing disciplines, the highest proportion of civil and environmental engineers considered sustainability to be essential, at 26%; this is also the only discipline where no respondents indicated a negative attitude towards sustainability (see Figure 4.6). Sustainability practice was shown to be equally essential for all of the disciplines. Electrical, electronics, and software engineers were the disciplines with the highest dislike toward sustainability, with 8% saying it was only marginally important in their personal lives.

Students' attitudes towards the triple bottom line of sustainability (i.e. social, economic, and environmental) in connection to their discipline were nearly uniformly positive. With rare exceptions, the majority of disciplines regarded each area as equally significant. According to Figure 4.7, civil and environmental engineering students regard the environment to be the most significant component of their studies with 28.57% of respondents. Chemical, material, mechanical, electronics, and software engineers found the environment equally significant, with all groups being 21.43%. However, electronics and software engineering students place a lesser priority on the environment and prefer to focus on social concerns (23.47%) when it comes to tackling sustainability difficulties in their respective engineering disciplines. Additionally, it can be observed that the

Figure 4.6

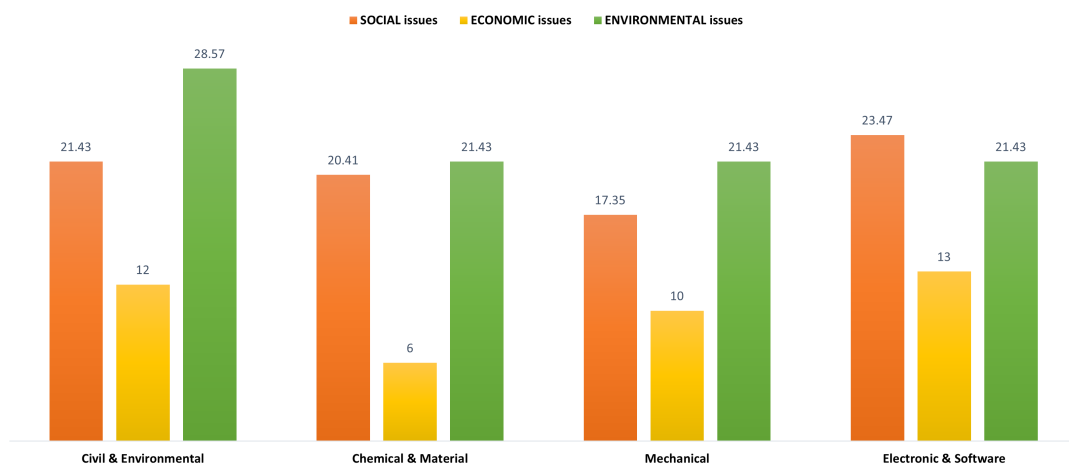
Respondents personal perception of the value of sustainability



majority of the disciplines shared a similar perspective on economic challenges; they all saw economics as equally critical, but not more so than the environment and social components of sustainability. Electronics and software engineering included the highest percentage (13%) of respondents who selected economy.

Figure 4.7

Respondents' perspectives on the importance of the Triple Bottom Line of Sustainability in their discipline

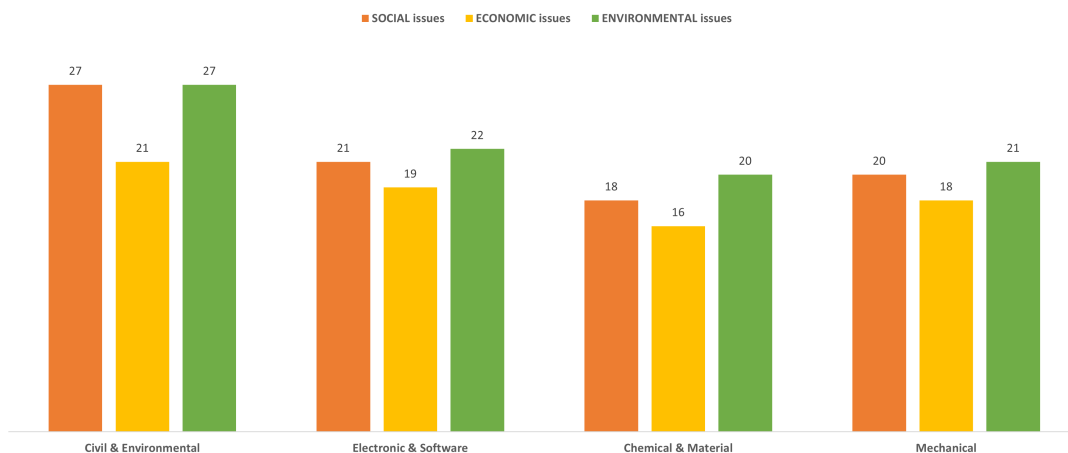


Students were also asked to rank the sustainability triple bottom line in order of significance, without consideration for their subject of study, and instead judged by their personal life. The data, as depicted in Figure 4.8, shows that students from practically every discipline place high priority on social concerns, almost as high as environmental concerns. This was not true when the focus was on

their disciplines (see Figure 4.7). Interestingly, the relevance of economic concerns has also grown. The findings suggested that all disciplines considered the triple bottom line equally vital, and they don't wish to discriminate between its elements. Figure 4.8 shows that civil and environmental students regard both environmental concerns and social issues as equally significant, with 27% for both categories. As with the discipline-based concept of the triple bottom line, the disciplines of electronics, software, mechanical, chemical, and material engineering deem environmental concerns equally essential. The most obvious trend is the shift towards economic concerns, with civil and environmental engineering students showing the highest percentage.

Figure 4.8

Respondents' perspectives on the importance of the triple bottom line in their personal lives



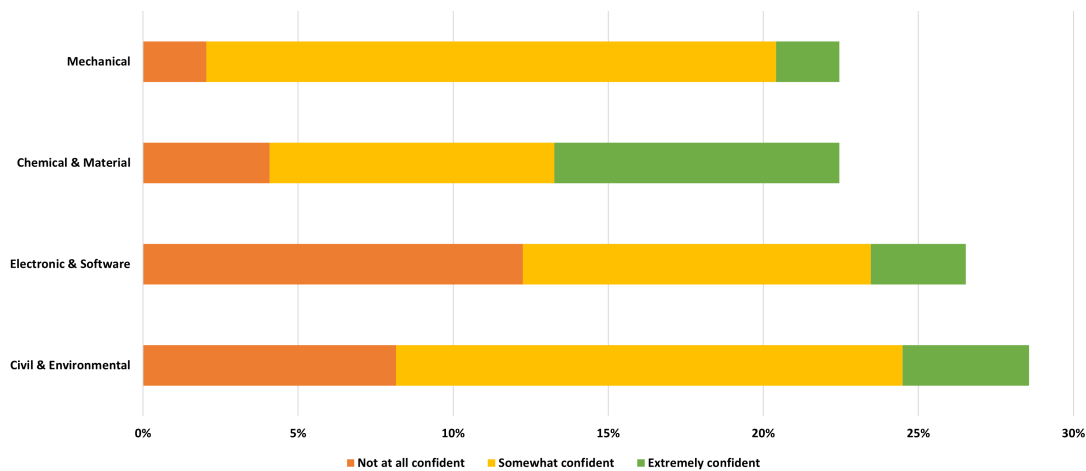
4.4.3 Confidence in Learning Sustainability

Students were unsure whether the material covered in class was applicable to their respective specialities. Students were asked if they have high level of confidence that what they have learned about sustainability in their disciplines is relevant to them. A significant number of students expressed uncertainty about the applicability of the knowledge they have acquired to their respective disciplines (see Figure 4.9). Electronics and software engineers are among the categories with the largest percentage (23%) of respondents who expressed a lack of trust in their discipline's ability to learn about sustainability. Chemical and material engineers are the only group that showed a high level of confidence

(9%). Interestingly, civil and environmental engineering students are also less confident, with 8% being not at all confident. After them, mechanical with 2%, and chemical and material with 4%, report being not at all confident.

Figure 4.9

Respondents confidence in their ability to learn about sustainability in regard to their discipline

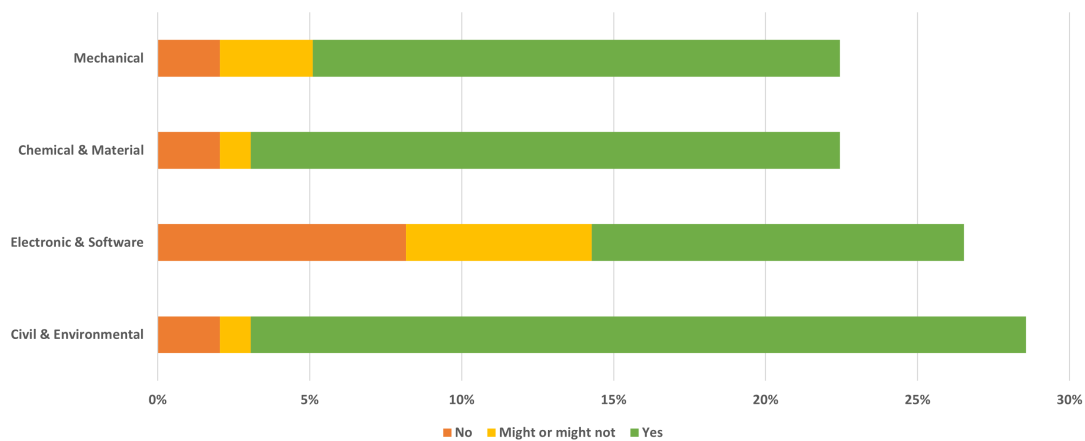


4.4.4 Environmental Science Relevance

The students were questioned about the relevance of environmental studies, and their responses are given in Figure 4.10. The majority of disciplines, including civil and environmental (26%), chemical and material (19%), and mechanical (17%) engineering, believe that their fields are inextricably linked to environmental sciences. However, electronics and software engineers find little to no relevance for environmental studies in regard to their respective fields. As seen in Figure 4.10, around 15% of electronics and software engineering students have said that there is no relevance. In comparison for students of civil and environmental engineering, only 2% indicated there was no link.

4.4.5 Interest in Sustainability

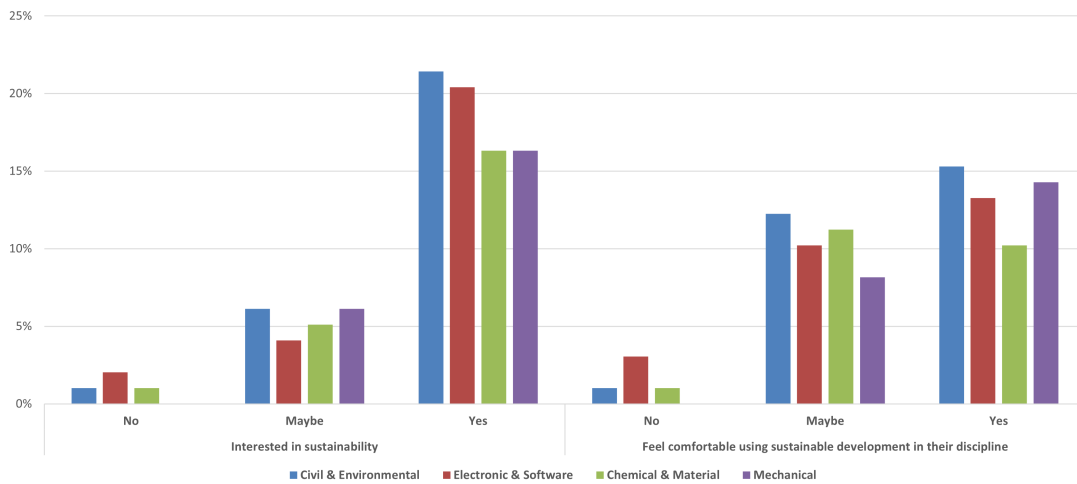
Students were asked if they are interested in sustainability. Civil and environmental engineering students were the highest percentage of respondents that

Figure 4.10*Environmental relevance for various engineering disciplines*

are interested in sustainability, with 21% indicating interest, followed by electronics and software, with 20% of respondents showing high interest in sustainability. Chemical and material, as well as mechanical, engineering students are both at 16%. However, this interest does not mean that they are comfortable with that they have been taught. Figure 4.11 represents the difference between respondents' personal interest in sustainability, and how comfortable they feel using sustainable development in their discipline. As this figure shows, students' comfort with using sustainable development in their discipline is often substantially lower than their personal interest. This is especially the case for civil and environment, electronics and software engineering student respondents. The difference, as shown in Figure 4.11, is not extreme, as not many students picked a negative answer. They are mostly unsure about the connection between their discipline and sustainability.

4.4.6 Different world views

Respondents were asked to identify whether their world view changed as an engineer when introduced to the notion of sustainability. Figure 4.12 depicts the respondents' answers. All of the groups had a favourable outlook and claimed that they had noticed a shift inside themselves. They have mentioned that their behaviour and decision-making as engineers has subsequently been favourably influenced. The only unexpected finding from Figure 4.12 is for chemical and material engineering students, where the number of respondents who say they

Figure 4.11*Respondents' comfort and interest in sustainability engineering*

have experienced change, and the number not sure whether they have changed, is equal. Electronics and software engineer respondents are the biggest category for which respondents are not sure whether the shift has happened or not.

Students were surveyed on the perceived difficulty of the topics/concepts they were studying in class. These topics/concepts (Figure 4.13) were derived from the publicly accessible paper outline. The majority of students had no difficulties during the paper. Figure 4.13 and Table 4.2 depict the participants' responses. As seen in Figure 4.13, the only topics that students found difficult were "Carbon Accounting," "Environmental Law and Regulations," "Life Cycle Assessment," "Resource Management Act," and "Environmental Impact Assessment". As can be observed from Table 4.2, the most often selected response for the aforementioned topics is "Somewhat difficult" (Mode of 4). However, the rest of the concepts are "Easy" (Mode of 1).

4.4.7 Troublesome concepts

Deeper analysis of the dataset was necessary to identify the most difficult concepts for each discipline separately. Figure 4.14 represents the previously indicated concepts that were found to be challenging by students based on their disciplines. From what we can see in Figure 4.14, LCA has proven to be a challenge

Figure 4.12

Comparison of survey responses on perspectives after completing the sustainability paper

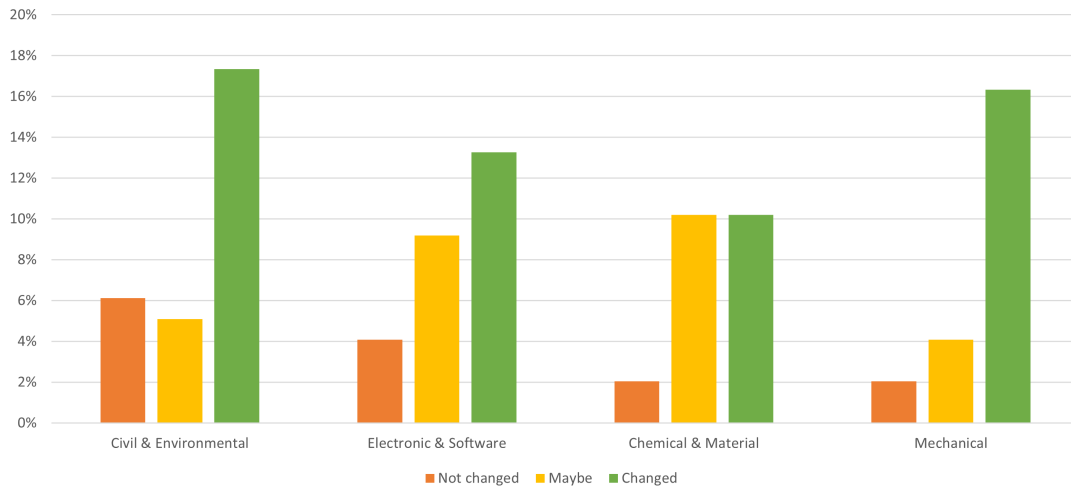
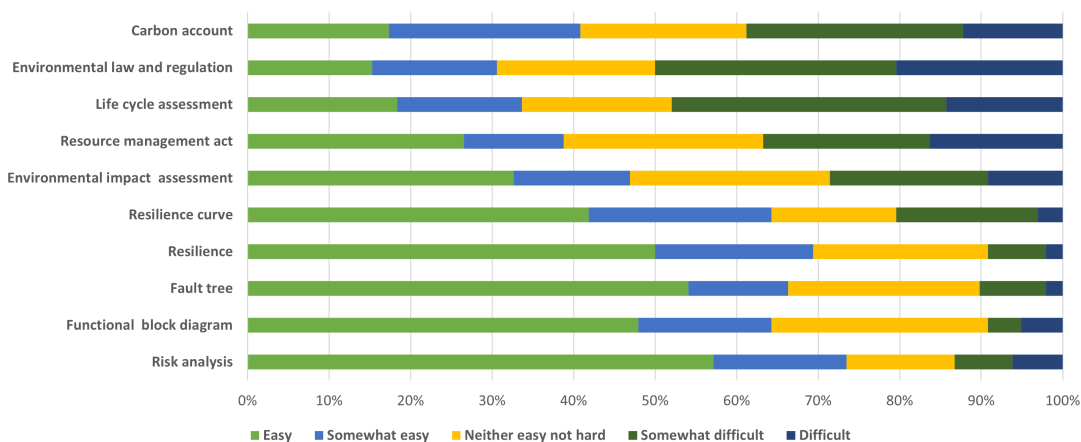


Figure 4.13

The ranking of sustainability engineering topics based on students' perception of their difficulty



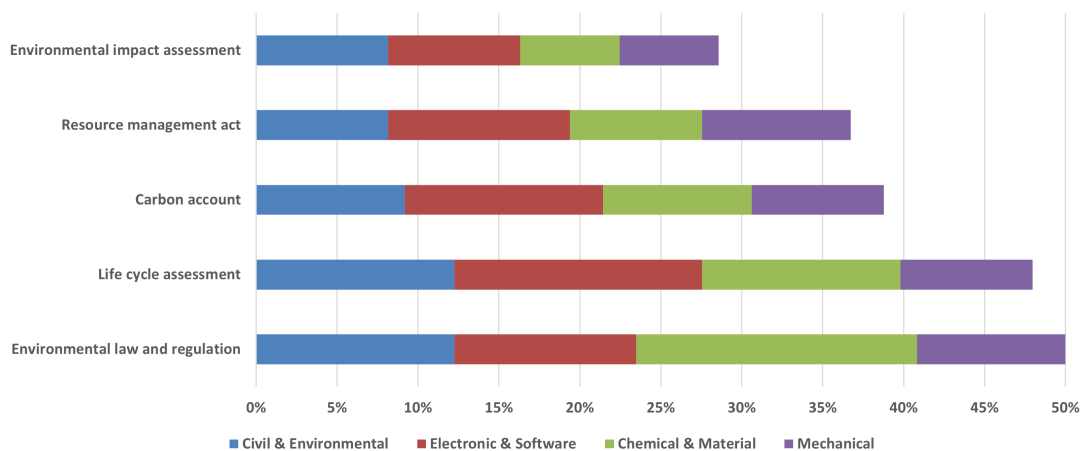
across the board. Almost every discipline found **LCA** equally challenging. The carbon account's distribution resembles the **LCA**'s in many ways. Additionally, the carbon account and the **LCA** should be treated as a single notion because they both, in a way, look at the carbon count of a specific product/project.⁸ **EIA** was chosen as the least challenging topic in Figure 4.14, whereas environmental law and regulation was chosen as most challenging.

⁸Students indicated that the carbon accounting and **LCA** were taught as one concept during our focus group.

Table 4.2*Descriptive statistic of covered topic in the paper*

		RA	FBD	FT	R	RC	EIA	RMA	LCA	ELR	CA
N	Valid	98	98	98	98	98	98	98	98	98	98
	Missing	0	0	0	0	0	0	0	0	0	0
Mean		1.89	2.02	1.92	1.92	2.17	2.58	2.88	3.1	3.24	2.93
Median		1	2	1	1.5	2	3	3	3	3.5	3
Mode		1	1	1	1	1	1	1	4	4	4
Std. Deviation		1.24	1.18	1.14	1.09	1.24	1.36	1.43	1.34	1.36	1.3
Range		4	4	4	4	4	4	4	4	4	4
Minimum		1	1	1	1	1	1	1	1	1	1
Maximum		5	5	5	5	5	5	5	5	5	5

Guide: RA: Risk analysis, FBD: Functional block diagram, FT: Fault tree, R: Resilience, RC: Resilience curve, EIA: Environmental impact assessment, RMA: Resource management act, LCA: Life cycle assessment, ELR: Environmental law and regulation, CA: Carbon account

Figure 4.14*The perception of sustainability's value by discipline*

Looking at each discipline in particular, it is clear that mechanical engineering students (8%) have the least challenging experience with **LCA**. However, electronics and software engineering students (15%) are the disciplines that found **LCA** most challenging. Surprisingly, chemical and material engineering (17%) students have the highest percentage when it comes to finding environmental law and regulation challenging.

4.5 Chapter Summary

The following chapter outlines the outcomes of the study, covering all phases. The main themes that emerged were discussed, revealing that participants emphasised discipline-specific concepts more than anticipated. A deeper understanding of students' comprehension and perspectives on engineering sustainability was achieved through a detailed analysis of responses from each phase.

This chapter summarised how students view sustainability education in their fields of study. The research found that identifying key concepts in sustainability education requires careful analysis of the subject-specific concepts.

Discipline-specific sustainability concepts were found to be influenced by students' perceptions. Variations in these concepts across disciplines were not immediately apparent, likely due to contextual factors such as the level of emphasis placed on sustainability topics and students' familiarity with related concepts. It is, therefore, crucial to consider these factors when designing sustainability curricula and promoting interdisciplinary understanding.

The research findings discussed in this chapter will be elaborated on in the subsequent chapter.

Chapter 5

Discussion

5.1 Chapter Overview

This chapter combines the research findings described in Chapter 4 with the literature presented in Chapter 2. This chapter aims to answer the research questions posed by this study, which were intended to investigate students' perceptions of sustainability and to identify threshold concepts in engineering education for sustainability education.

Using an interpretivism paradigm and phenomenography methodology, it was possible to gain insights into the sustainability threshold concept in this study. This approach encapsulated the perspectives of several students and a lecturer on "sustainability". To answer the study's research questions, multiple data collection sources were used, including interviews, document analysis, and questionnaires.

This chapter is divided into four sections. The first section discusses the unique model developed for this study. The model is an enhanced version of the model described in Chapter 2. It enables a better understanding of students' perceptions using threshold concept theory and liminality. The remaining sections expand on the themes introduced in Chapter 4. Each section includes a brief description, explanations, interpretations, and exemplifications of the findings, as well as discussions of the connections between these findings and published research to answer the research questions.

5.2 Spatio inter limina: The Study's Model

This section, Spatio inter limina, translates directly to “a space in between the threshold”. Spatio inter limina is an original model that was developed using this study's findings. Following [Threshold Concept Theory \(TCT\)](#), [liminality](#), [phenomenography](#), and [my findings](#), I created a model to aid in interpreting participants' perceptions within their discipline. In the first part, the model is explained without any examples. The model is showcased in the second part of the section, which incorporates different disciplines to illustrate students' understanding of a concept covered in the sustainability paper.

[TCT](#) posits that certain concepts within a discipline have transformative qualities, but grasping them can be challenging. This process of internalizing a threshold concept can be seen as a transition from one state of knowledge to another, which [Meyer and Land \(2005\)](#) refer to as “liminality” or “liminal space”. According to [Meyer and Land \(2003\)](#), the threshold concept can be defined as akin to a portal, opening up a new and previously inaccessible way of thinking about something.

This study focuses on the collective experiences of diverse engineering disciplines. In order to develop this model, the multiple transcripts collected as part of this research were combined into a single comprehensive document. All participants' perspectives were considered, not as individual views, but as a collective mindset. This collective mindset was used to create a shared understanding of the engineering experience, which accounts for the diversity of voices in the research.

Given that this study uses phenomenography and has a large sample size with a collective viewpoint, rather than relying solely on individual perspectives, this research approach allows for a complete understanding of the lived experience of the collective viewpoint. However, because of the small sample size across all engineering disciplines, the model established in this study cannot be regarded as a definitive system.

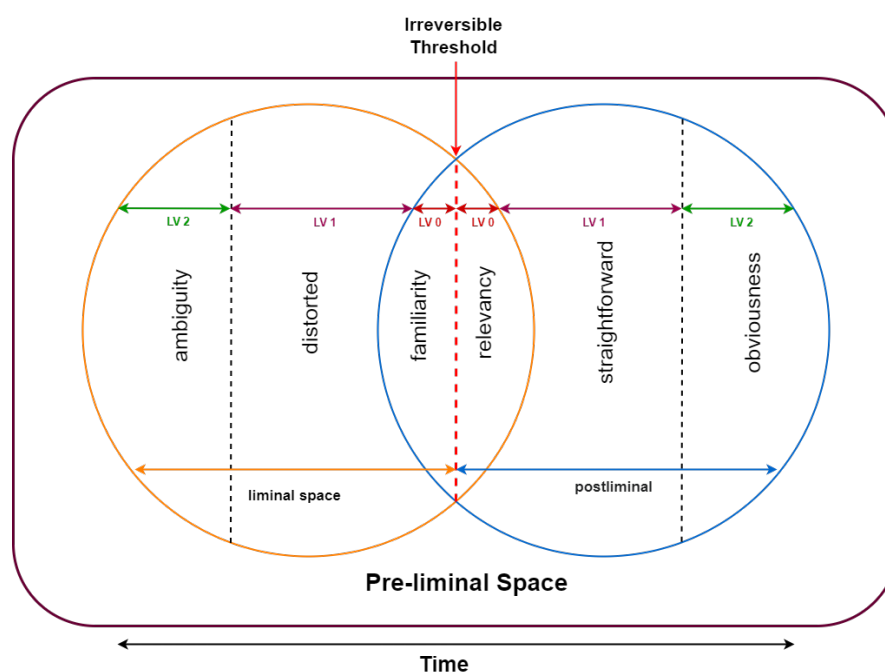
[Marton \(1986\)](#) describes phenomenography as “whatever phenomenon we encounter” as “it is experienced in a limited number of qualitatively different ways”. This means that, while the model is useful as an example of what is possible in

engineering education, it should not be considered a definitive answer, and more research is required to ensure the accuracy of the findings.

A model was necessary to understand the findings better, given the large and diverse nature of the data. The model looks closer at the liminality tunnel, which has mostly been portrayed as a difficult journey. However, after a thorough search of the literature (Kabo and Baillie, 2009), what happens in the tunnel still needs further development. This model can shed light on the liminal tunnel (Figure 2.3). The learning journey is supported by the spatio inter limina model, as demonstrated by Kabo and Baillie (2009) and Rattray (2016). Figure 2.3 shows how this model maintains the learner's journey, where one student may have an easier time grasping the material, while another may have a much more challenging time. The model therefore accommodates variations in the educational path taken by different students.

Figure 5.1

Novel liminal model of learning - The model was inspired by TCT and liminality space, and was developed through the findings in this study



The model, as illustrated in Figure 5.1, represents both liminal and post-liminal space on the preliminaries plane. Pre-liminal space occupies pre- and post-liminal stages since it is impossible to know whether learners have passed the threshold before introducing the concept. The model suggests that students may have a firm grasp of the material or know nothing. Ultimately, the path a

student takes through a course is not visible to the educator. From the learner's perspective, they will not have any clue whether they have passed the threshold unless the concept is presented to them by the lecturer.

The role of time is an essential aspect of this model. While the model does not explicitly depict time flow, it can be imagined as moving along the X-axis. The model is influenced by the passage of time because it provides a context in which certain events can occur. However, the model is static for educators, assuming they have already mastered the concept. The model is dynamic for students, as they are introduced to new concepts that can either help them overcome the threshold or cause them to become more confused. According to the [TCT](#), the role of time in this model is not always clear-cut, as some students may be stuck in liminal space and still pass their courses. I will further explain each level and how time is relevant in both liminal and post-liminal space as I discuss each level in more detail.

Both liminal and post-liminal space have three levels, each representing a different state for the learner. Starting with liminal space, level 2, the learner has no idea what the concept is trying to convey. They experience a sense of uncertainty and loss, and the concepts are hazy and ambiguous. The learner at this level can comprehend that the paper is trying to communicate something, but the concepts will make no sense and may feel out of place. Therefore, the learner will feel angry, fearful, and stressed because they cannot escape. At this stage, time is essentially meaningless to the learner because they still need to develop the understanding or agency to perceive and manipulate the concepts. As a result, attempts to use time as a measure or motivator may be ineffective or even more confusing.

When the learner reaches liminal space level 1, they have a better understanding of the material, but it is still hazy and incomplete. Despite this, they will likely recognize some familiar elements within the material, although the overall concept has yet to reach a point where it can be fully understood. The student may feel overwhelmed and perplexed by the amount of information and work required to comprehend the concept thoroughly, and may notice the passage of time more at this level due to the energy and effort required to progress through it.

Liminal space level 0, before being transformed (irreversible gate), is where concepts are familiar and feel closer to what learners already know. The learning

experience at this level is more aligned with what was expected before starting the journey, but it may not necessarily be beneficial or bring about significant progress. It may even mimic what learners expected to learn or have already learned. As a result, learners may not see time spent at this level as essential or valuable if their primary goal is to pass a paper or test. However, it is important to note that this level is considered the starting point for the learning journey and is necessary in order to move on to more advanced levels of understanding and comprehension.

When learners cross the irreversible threshold, they enter the first level of post-liminal space (relevancy). In this state, learners find the concept relevant and their knowledge applicable and meaningful. As a result, because they have passed the irreversible threshold, the knowledge does not appear alien any more. Like the previous state, time is constant here, since learners were able to pass the threshold. Once they are familiar with the concept, it becomes more straightforward.

Level one in post-liminal refers to the learners' evolution and increased comfort with the knowledge they have gained. This level represents concepts that are easier for students to understand and retain. These concepts can be applied in various areas (other papers) if desired, as the learners have gained a strong foundation. However, it is important to note that it will take a considerable amount of time and energy for learners to progress to the next level, as they will need to continue to absorb and integrate the new information.

The learner will achieve complete mastery of the concept at the final level of post-liminal space, where using it would feel natural and without challenge. It is important to note that level two post-liminal space knowledge, a highly advanced understanding of the unconscious mind and its effect on behaviour, can only be obtained through consistent repetition and years of dedicated practice.

This level has a more severe interaction with time, meaning that mastered concepts will be forgotten over the years unless consistently practised. This does not mean that the concept will be completely new and unfamiliar; rather, it will take some time and practice (less than the first time) to regain mastery. For example, a teenager who can ride a bike with no hands is the master, but over time as he ages and does not ride the bike regularly, it will be harder to ride with no hands. However, if he practices for a while, he can ride it with no hands again.

In the following section, I will show the model's use and how it helped analyse students' perceptions of **FTA** across multiple disciplines. Each discipline, according to its understanding, will be placed on a different stage of the model, showing how their understanding alters their perception of sustainability.

Spatio inter limina: illustration

The use of **FTA** as an example to better illustrate the model could help provide sufficient background information to comprehend the model. According to the questionnaire results in Figure 4.13, participants found the **FTA** family of concepts to be the least challenging (Section 4.4.7). Concepts such as resilience, fault tree, functional block diagram, and risk analysis were identified as not troublesome. Following **TCT** characteristics, **FTA** would have been eliminated as a viable concept to be a threshold concept, and any further study would have been cancelled. However, participants in focus groups and interviews had different perceptions. Disciplines of **MPE**, **ME**, **SE**, **EEE**, and **CE** (5 out of 7 disciplines) found **FTA** to be a beneficial concept (Section 4.2.2).

Discovering **FTA** to be both an easy and beneficial concept caused me to realise that there has to be something more. **FTA** was mentioned many times during interviews as a beneficial concept, which meant it was memorable. Being easy and memorable at the same time seemed contradictory. Therefore, **FTA** had to be covered in another course, which made it beneficial and easy at the same time.

Furthermore, students were able to explore **FTA** from the comfort of their disciplines, developing a better understanding of the implications it could have on sustainability and their respective disciplines. With the new awareness of **FTA**, students were able to look at their disciplines from a different perspective.

The spatio inter limina model (Figure 5.1) could be used to interpret students' perceptions and provide insight into how they felt. According to the model, **CE** and **MPE** have discovered a clear link between their disciplines and **FTA** (**post-liminal straightforward level**) as pointed out by Condan and Thaddeus (Section 4.2.2). They found **FTA** beneficial since it can help with long-term planning and accident prevention. Their understanding of **FTA** is in line with the sustainability

definition and importance of system thinking in sustainability (UNESCO, 1987; Loringa, 2020; de Haan, 2006).

The use of FTA was utilised by participants to illustrate their system thinking and intent to avoid accidents in their projects. In terms of sustainability, it is clear that MPE and CE were able to connect FTA to the requirements of their respective disciplines. This shows that they were able to pass the threshold and to connect several domains. Furthermore, Aldona (a CE from a different group) also clearly illustrates the relevance she found with FTA. Aldona explains and shows her threshold moment as the lecturer was discussing past case studies in which FTA could have prevented death and destruction (Figure 5.2).

Figure 5.2

Illustration of participants and their perspectives on FTA using the spatio inter limina model

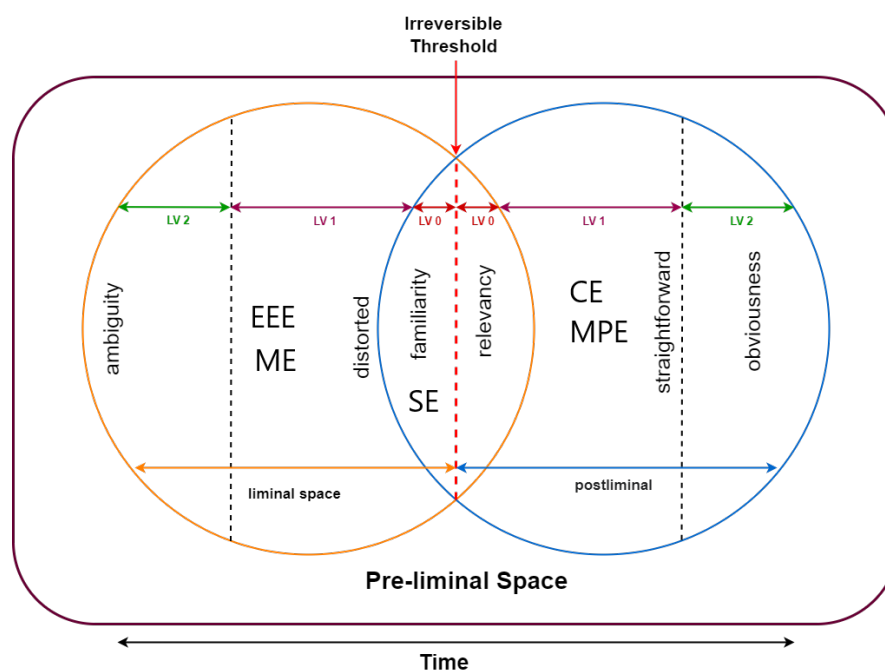


Figure note: According to the findings, some disciplines have already crossed the threshold, but others were unable to identify any relevance between their disciplines and FTA.

However, the EEE, SE, and ME students perceived FTA to be mostly familiar and, at most, relevant. Hugo, Cody, and Aragon found FTA useful, but not for the same reasons provided by the CE and MPE students. They never once mentioned how FTA could be beneficial in their projects or for sustainability, but rather they mentioned how closely related it is to Boolean logic (a discipline-bounded concept), which they learned in their first year in electrical and electronics coursework.

Participants from **EEE** and **ME** provided distorted interpretations of **FTA** since they were never able to describe why it is a valuable concept, particularly in a sustainability paper, or how it may be implemented in their disciplines (**EEE** and **ME** are in distorted liminal space as shown in Figure 5.2).

The only participant from the **EEE** group who passed the threshold is Dehirm, who has already used **FTA** in his work numerous times, albeit under other names (threshold concept and terminology).¹ Dehirm also approaches **FTA** with allusions to how he is familiar with it, explaining that he would have benefited more from the **FTA** approach if it had followed the same naming system as he was used to, but he does give us a little glimmer of hope by pointing out that the **FTA** could help with protecting what is physically in our control (a clear link to sustainability).

SE, on the other hand, were more clear as to why **FTA** is beneficial. Meinrad, with the support of other **SE** members, mentioned how **FTA** could be used in a certain aspect of software engineering to prevent accidents and set up redundancy. At first glance, it is evident that they have passed the threshold; however, they are mimicking a concept from their discipline-specific paper.² That makes **SE** in the familiarity level within liminal space.

In summary, respondents from five out of seven disciplines considered **FTA** principles beneficial, even though it was rated the least challenging in the questionnaire. **FTA** would have been ignored as a threshold concept in accordance with **TCT**. The data from interviews and focus groups showed that the real threshold concepts are within **discipline-bounded concepts**, which could help students understand sustainability in their disciplines. Following the **FTA** example, it became clear that certain disciplines have crossed the liminality gate, while others are only mimicking what they learnt in past paper. For example, **CE**, **MPE**, and **SE** have discovered a clear link between their disciplines and **FTA**. Whist **ME** and **EEE** disciplines could not find any link between **FTA** and sustainability in their disciplines. The following section demonstrates and covers one of the study's paradoxical findings, demonstrating the use of this model and how the collective viewpoints of participants could be incorporated with the help of this model.

¹Meyer and Land suggest that the crossing of a threshold will incorporate an enhanced and extended use of language.

²This statement is supported by all **SE** participants where they found Pyrrhus' paper to be more relevant (Section 4.3.3).

5.3 Life Cycle Assessment: A Paradox in Threshold Concept Theory

Life Cycle Assessment (LCA) has the ability to be both a threshold concept and not a threshold concept. The distinction relates to the order in which it is introduced to students. If LCA is introduced to first-year students, it has the potential to change their perspective. When presented to higher-level students, however, it has the reverse impact. In this section, I will discuss why LCA presents such a conundrum in engineering education by being both difficult and easy simultaneously (Figure 5.3).

The only troublesome aspect of the paper analysed for this thesis was revealed to be LCA. The questionnaire identified it as the most challenging component (Figure 4.13), and this was also acknowledged by the majority of interview and focus group participants (among third and fourth-year engineering students). Furthermore, LCA was regarded as challenging by first-year students based on document analysis of their reflections.³

Participants in this study described LCA as broad and vague while also detailed and complicated. The data revealed students experience LCA as depending too much on assumptions and estimations, leaving students uncertain about their findings. Both junior (first-year) and senior engineering (third- and fourth-year) students were uncertain about their findings and would have appreciated a more definite conclusion. The source of the uncertainty was ultimately discovered to be data collection, system boundaries, and assumptions. The course's impact on the junior engineers' outlook was the most striking distinction between them and the senior engineers. There is a significant gap in understanding of LCA between senior engineering students and their freshman counterparts. Both parties agreed on LCA challenges, but they couldn't agree on whether or not LCA was genuinely transformative.

Junior students struggled with concepts such as system boundaries, estimation, and data collection. Senior engineering students also reported similar difficulties. Dehirm, for example, correlated LCA with phrases like "broad scope", "detailed and comprehensive", "dense topic", and "dealing with jargon terminology". All of the participants' anger towards LCA is evident, and the results of

³Cf. Section 4.2.2

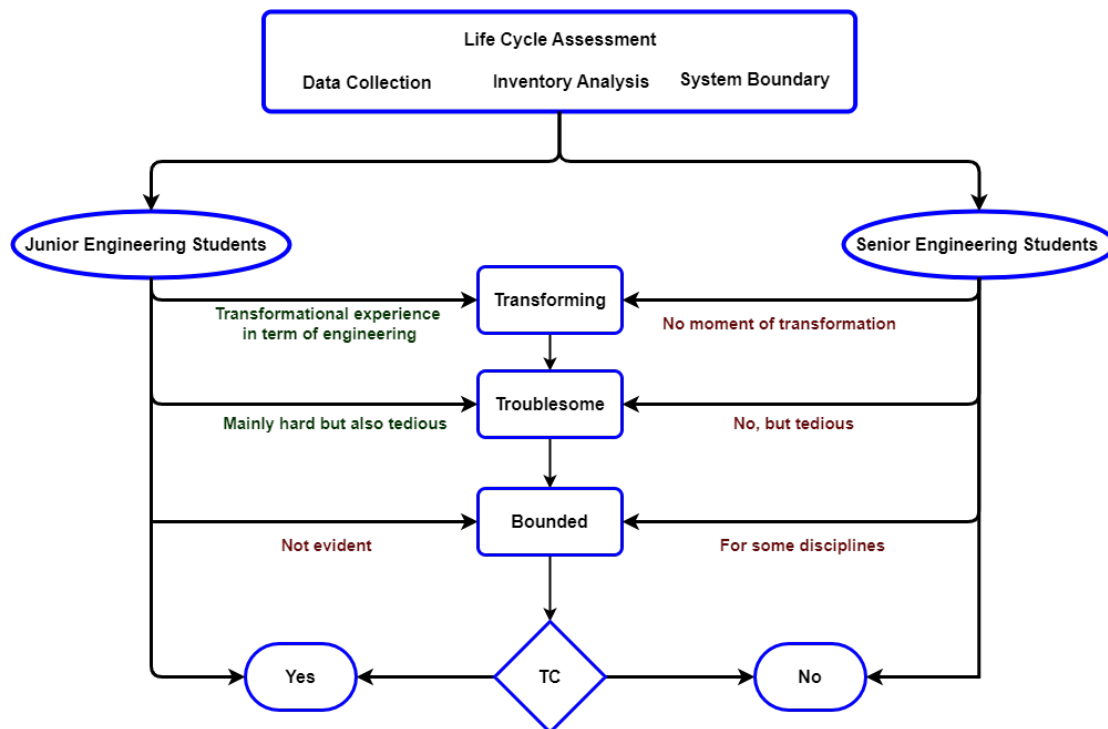
Figure 5.3*Paradoxical nature of Lifecycle Assessment in sustainability*

Figure note: The diagram summarizes how senior and junior students perceive LCA through analyzing different TCT characteristics.

the questionnaire (4.13) emphasise this even more. Furthermore, the assertions made by the participants are consistent with prior research (Strobel et al., 2010; Lloyd and Ries, 2007; Malkki and Alanne, 2017; Bjorklund, 2002).

LCA was proposed as a threshold concept by both Strobel et al. (2010) and Weber et al. (2011). In addition, it was mentioned that it is extremely complex and unpredictable (Bjorklund, 2002; Reap et al., 2008; Lloyd and Ries, 2007). The International Organisation for Standardization's (2006a) LCA framework provides practitioners with great flexibility and independence. As a result, different LCA reports on a project tend to include different numbers, making it hard to find an LCA report as a reliable reference (Lloyd and Ries, 2007). Furthermore, data acquisition and the absence of data on specific topics force practitioners to estimate and assume quantities (Bjorklund, 2002; Lloyd and Ries, 2007).

While estimation is a standard industry practice, students are not yet experienced with this practice. The data showed that first-year students had trouble estimating data for their reports, even though they had a ready-made database.

Given their abilities and the fact that they were fresh high school graduates, the project was not intended to take too much time, and most data was provided for them. However, because senior engineering students were more skilled and worked in groups, they were expected to submit a detailed report. Consequently, as highlighted by [Lloyd and Ries \(2007\)](#), the inaccuracy of the data caused students anxiety and left them wondering whether they had done something incorrectly.

The complexity of [LCA](#) is not necessarily problematic in engineering education. [Malkki and Alanne \(2017\)](#) mentioned that teaching complex concepts/systems in sustainability would enable students to familiarise themselves with real systems before they graduate. That is why [LCA](#) and [Life Cycle Thinking \(LCT\)](#) have been introduced in the engineering curriculum to help students to design a well-planned product and conduct comparative analysis ([Malkki and Alanne, 2017](#); [Naumann et al., 2011](#)). [LCA](#) could also influence the student's system thinking skills. System thinking has been introduced as one of the competencies in engineering education and sustainability education; it is also recognised as a threshold concept in sustainability ([Loringa, 2020](#)). Evidence from both my research and published work therefore supports the finding that [LCA](#) is a threshold concept.

I agree that [LCA](#) is a threshold concept in its own right, as pointed out by [Weber et al. \(2011\)](#), and that it has the potential to be a threshold concept in sustainability education for engineers at the early years of undergraduate level as pointed out by [Strobel et al. \(2010\)](#). With that said, even though I see the importance of [LCA](#), I do not believe it can serve as a threshold concept for senior engineering students.

Firstly, not all disciplines found [LCA](#) difficult. [ME](#) and [CHE](#) found the entire process to be simple and easy to follow.⁴ Secondly, in engineering education, [LCA](#) looks to be an oxymoron, particularly in disciplines where interaction with environmental analysis is minimal.

⁴For these students, [LCA](#) was not a troublesome concept but tedious, which will be further discussed below.

The reasoning behind not accepting [LCA](#) as a threshold concept for senior engineering students ultimately stems from the understanding that threshold concepts are positioned inside each discipline (Section 5.4). Only because disciplines like [ME](#) and [CHE](#) had already been prepared to deal with “models”, “material flow analysis”, and “system boundaries” did they find [LCA](#) so simple. As a result, it can be inferred that, according to the [research model](#), students in these disciplines have previously passed the threshold, and it has aided them with [LCA](#). [SE](#) and [EEE](#) students, on the other hand, felt alienated because they had never been exposed to these principles.

Since [LCA](#) was found to be tedious, it further encourages me to believe that it is not a threshold concept. The main reason why participants in this study found [LCA](#) troublesome was its tedious nature. Many noted how time-consuming and tedious it was to find relevant data for their projects. [Reap et al. \(2008\)](#) raises similar concerns about [LCA](#)'s problematic nature, and their findings highlight the same issues. Interestingly, while both junior and senior students found [LCA](#) tedious and troublesome, only junior students felt transformed by it.

All the positive and negative aspects of [LCA](#) were an excellent introduction to the engineering world for first-year students. While they were annoyed at first, they found [LCA](#) to be transformational by the end of the course. I am confident that first-year students' transformations were genuine and that what they felt after learning about [LCA](#) and sustainability may be a threshold concept moment. [Strobel et al. \(2010\)](#) obtained comparable results from first-year engineering students; however, the same result cannot be found for senior engineering. Strobel et al.'s (2010) study did not focus on sustainability in engineering, and his participants were not at a higher level. The senior engineering students remarked that the entire procedure was tedious, with no moment of transformation. Certain disciplines, such as [SE](#) and [EEE](#), were more susceptible than others. A great deal of study has demonstrated the problems and uncertainty associated with [LCA](#) ([Bjorklund, 2002](#); [Mulder, 2017](#); [Lloyd and Ries, 2007](#); [Reap et al., 2008](#)).

According to the research model, senior engineering students did not experience any transformation since there were no opportunities to make the concepts in the paper feel familiar. That suggests they are stuck in level three of the [study model](#) with no hope of passing the threshold. This assessment also confirms

Weber et al.'s (2011) findings that suggest an unrelated LCA project to be a leading source of challenge for most students. Weber et al. (2011) found unrelatedness to be one of the most important thresholds, and suggested that it would make the journey for students more pleasant if they could relate the projects to their disciplines. Therefore, with the model in mind, it can be shown that EEE and SE could not find any familiar concept to hold onto so that they could pass the threshold. This evidence again further emphasises the importance of discipline-specific sustainability education, which will be further discussed in the next section.

Another reason I endorse the approach of discipline-specific sustainability education is the way software disciplines perceive LCA (Section 4.2.2). The results revealed that the link between LCA and SE is one-sided. That is, software engineers were not interested in incorporating LCA into their papers and often struggled to see how it was relevant to their discipline. They emphasised how ineffective LCA is for them. Surprisingly, they were not discussing the framework of LCA, but rather how LCA was taught. The data showed that SE took environmental issues not as seriously as other disciplines, yet they were conscious of how important their field is regarding sustainability challenges. They understood the importance of environmental impacts and their role in the industry. Their problem mainly originated from a lack of relatedness to their discipline.

Furthermore, the spatio inter limina model can be used to interpret the perceptions of SE participants once more. As stated on Page 200, the only way for students to cross the threshold is to feel acquainted with concepts in the paper. According to the data, SE participants could not find something familiar to their discipline in LCA. A number of the SE students complained that they did not understand the environmental issues that were being discussed in class and that LCA therefore appeared to be irrelevant (Section 4.2.2). They are aware of the significance of their sustainability field, making the disconnect between what they are learning for their degree and what they are doing to learn about sustainability seem more significant.

As SE students did not encounter anything they recognised, no threshold crossing transpired. Without this transforming quality, concepts appear tedious. Pyrrhus⁵

⁵Pyrrhus was evaluated by SE students to have the best paper that is akin to sustainability in software engineering.

also mentioned a lack of familiarity, arguing that the LCA being taught is irrelevant. He also brought up concerns about the educational system, including that courses are designed by civil engineers for civil engineers, while students from other disciplines are required to master irrelevant concepts in their disciplines.⁶

Pyrrhus promoted the idea of making LCA relevant (or, at the very least, familiar) to SE students. The study's findings suggest that software systems can be classified into three phases: design; operation; and maintenance. The key distinction is the non-visible maintenance phase, which is not evident in the same way as it is for most other systems. As a result, the maintenance phase of software systems has a substantially bigger environmental impact. Users, in particular, are usually unaware of what is happening behind the scenes; as Pyrrhus points out, software is strongly dependent on hardware. Because software systems are relatively new as a field of study, they are among the most intricate systems in existence. Therefore, LCA in software engineering must be treated differently.

As was seen in Section 2.5, all product life cycles come to an end at some point. In traditional LCA, this means the product is either discarded, recycled, or reused. When it comes to software engineering, however, the end of life equals the end of maintenance. As a result, you can still buy or use the software, but there will be no more patches/updates.⁷ The ever-changing operations of software engineering have made keeping up with traditional environmental analysis techniques, i.e. LCA, unfeasible in educational institutions. Therefore, the tedious and alienated feeling that all SE participants had in this study was due to their LCA project not being related to their field. That is why Pyrrhus recommends teaching LCA to SE using concepts familiar to them, such as data centres, cybersecurity, or software methodological approaches.

In summary, this study found that there are problematic elements within LCA (i.e. system boundary, data collection, inventory analysis), as well as moments when certain participants (first-year students) demonstrated signs of transformation, and there is evidence of some disciplines finding LCA easy (e.g. ME and CHE). Furthermore, participants in this study have made certain inferences which are consistent with the literature. In light of this evidence and the developed research model, I have concluded that LCA has the ability to be both a

⁶He is grouping software, electrical, and electronics engineers together because their disciplines are more similar.

⁷Even though you may be able to purchase the discontinued software, it will not include any support.

threshold concept and not a threshold concept, depending on at which level it is being taught to students. LCA is a threshold concept for first-year students, but it is not for third and fourth-year students. Furthermore, I was able to highlight the importance of making sustainability education relevant to all disciplines.

The following section discusses another significant finding in this study, showing how the literature neglects discipline-specific concepts while favouring generic ones, and exploring a key concept in sustainability education—antithesis.

5.4 Discipline Specific Concepts: Antithesis in Sustainability

According to Meyer and Land (2003), one of the essential characteristics of TCT that can help identify threshold concepts is troublesome knowledge. According to the study's findings, what students consider troublesome knowledge is often simply tedious tasks when it comes to sustainability. Their dissatisfaction and frustration with the concepts offered cause students to view sustainability as troublesome knowledge. This study also showed that the essential characteristic that must be considered when it comes to teaching sustainability is boundness (Section 2.3). A critical finding of this study is that, according to engineering students, what literature perceives as essential knowledge is tedious. This section presents an alternative—antithesis in sustainability contrasts the literature with what students perceive.

The findings of this study reveal that all threshold concepts in sustainability are hidden within disciplines. In this sense, they are constrained, and students graduate without explicit awareness of their existence. Because these concepts have never been explicitly stated, students are unaware of the specific application of what they are studying in sustainability. Based on the findings, students are responsible for integrating sustainability principles into their fields of study without external guidance.

To ensure that all students graduate aware of threshold concepts in sustainability, the *spatio inter limina model* can be used to highlight the importance of relevance and familiarity when it comes to sustainability challenges. After all,

according to [Wilson \(2019\)](#), students are more motivated to perform better if they are emotionally connected to the material.

However, there are concepts concealed within each discipline that can be identified as threshold concepts in sustainability. The disciplinary boundedness of these concepts is consistent with the study's model (Section 5.2), which identified the familiarity and relevance to participants of the concepts represented. The implications of threshold concepts at a disciplinary level for sustainability education point to the necessity of introducing students to relevant discipline-specific knowledge and taking a multi-perspective approach to teaching sustainability as a cross-disciplinary subject.

The emphasis on student perspectives in this study's model will make the experiences of each discipline distinct, resulting in differences in the importance placed on certain concepts between disciplines. This means that it will be challenging to determine the position of each discipline unless they are briefed and questioned in detail. Further investigation is necessary before a final answer can be reached on the problems plaguing engineering education in sustainability. However, the findings discussed here are consistent with the study's model and the literature on discipline-specific notions of sustainability ([Penzenstadler et al., 2018; 2014; Venters et al., 2018](#)).

The literature on TCT and sustainability reviewed for this study deprioritised discipline-bounded concepts. Discipline-bounded knowledge values were neglected in favour of a laundry list of competencies that have no emotional value to students ([Wiek et al., 2011](#)). As highlighted by [Fisher and McAdams \(2015\)](#), understanding how introduced concepts and discipline-specific knowledge work together will lead to changes in the curriculum that will result in a better learning experience for students. It is important to remember that, according to the model, the transformation can occur only if the learner is already familiar with the concepts. Learners' emotional connection to discipline-specific concepts is strengthened by familiarity. Students can't pass through the liminal space and the learning threshold if there are no relevant concepts to help them emotionally, a finding also highlighted by [Wilson \(2019\)](#).

As discussed in Section 5.3, LCA was the most troublesome (tedious) concept in the sustainability paper; most disciplines found LCA difficult, except for Kairdra's discipline (CHE). In a paper where everyone else had issues with LCA, Kairdra

had no problems and found the whole process easy. “Because we had to do mass balance and energy balance”, she explained, “like intakes, out-takes, and how much flow is going through them”. Kairdra was familiar with this process because “mass balance” is mandatory in the CHE degree. However, others could not follow her steps because they were unfamiliar with mass balance.

Mass balance is one of the **bounded concepts** in this study and is associated with the CHE discipline. Following the **research’s model**, it is clear that Kairdra passed the threshold since she had to repeat mass balance every year in different disciplines’ specific papers. Furthermore, Kairdra was one of the few participants who found LCA easy due to her familiarity with mass balance. What helped Kairdra was how system boundaries, one of the most challenging aspects of LCA as confirmed by **Reap et al. (2008)** and **Bjorklund (2002)**, were overcome with the aid of mass balance. “Set system boundaries on your LCA”, she added, and then “analyse (it) like material flows”. Therefore, the relevance of mass balance to system boundaries helped her pass the threshold in the sustainability paper.

The ME discipline found that modelling and visualisation, a well-established concept in their field and, most importantly, relevant, helped their understanding of LCA. ME students found LCA’s detailed models and graphics easily interpretable in a real-world setting. For instance, Jenniye (ME discipline) struggled to make sense of the LCA diagrams and encountered “the difficulty with people receiving information, not knowing what it means, and falling victim to a beautifully drawn graph”. After outlining her thoughts in a diagram, Jenniye understood the LCA assignment. Indeed, modelling and interpretation, which could also be traced back to mass balance, allowed ME and CHE students to grasp LCA better than the other participants.

EEE participants named technology and design as the two main discipline-specific concepts that can promote sustainability in their discipline. Hugo, from the EEE discipline, said, “technology and sustainability are related, so the better the technology, the more sustainable you will be”. The negative effects of technology, and how it has changed so that smaller devices are no longer repairable, were also emphasized by EEE participants. According to EEE, one of the most effective ways to promote sustainability is to use innovative design in the way a device works and the components used for production. These findings are supported by **Smith (2009)** and **Hankammer et al. (2021)**.

Improving design and technology from the [EEE](#) perspective was mainly oriented to increasing efficiency. Therefore, [EEE](#) was the only discipline focused on automation. Due to their system-thinking abilities, they were able to see the connection between efficiency and sustainability, two goals that can be achieved through improved automation. Dehirm's vision of a sustainable future for [EEE](#) placed automation at the centre. According to Dehirm, automation was a possible strategy for improving the meat industry's sustainability through better design and technology. [EEE](#) participants argued that the sustainability paper's narrow perspective did not consider the broader function of their discipline. In other words, automation, design, and technology are essential aspects of the [EEE](#) discipline but were never mentioned in the sustainability paper.

Similarly, [SE](#) participants also found the paper irrelevant, mainly due to the inclusion of environmental laws. While they agreed that environmental protection is essential, they were dissatisfied with the paper's lack of relevance to their discipline. [EEE](#) and [SE](#) found the inclusion of environmental studies to be the least important in their disciplines. In their opinion, [EEE](#) and [SE](#) disciplines can help with sustainability issues by reducing waste and increasing efficiency. [SE](#) participants found algorithms to be a discipline-specific concept in their domain. They believed an efficient design would mean a better algorithm and a more efficient system. By writing better algorithms, it is possible to have a better-designed product, increase efficiency, and reduce waste, all of which can help with not only making more money but also protecting the environment. As a result, the environmental aspect is a by-product, rather than the primary goal of their discipline.

The best example of a unique discipline-specific mindset was given by Raynard, who described how, for their [LCA](#) assignment, they preferred to focus on writing a better and well-designed program than on the environmental aspects of constructing traffic lights. Their work suggested changing the traffic light system's software algorithm to decrease vehicle idling and lower carbon emissions. Unfortunately, it seems that the inclusion of better-designed algorithms was merely a suggestion and was not part of the main report. This shows that the software engineering students were frantically searching sustainability papers for anything relevant. However, all they could do was make connections between what they already knew and what was being offered, which made the process tedious.

This means that students either need to be provided with research directly related to what is required for their discipline or should be trained to adapt and adjust their work to the needs of any given project. The latter, of course, requires a paradigm shift and hard work to implement in a university with a neo-liberal mindset.

Yell (SE discipline) pointed out that his LCA project had nothing to do with software engineering and suggested concentrating on more meaningful projects, like data centres. Other SE participants, including Pyrrhus, agreed with Yell's proposal. The critical factor in data centres related to algorithms is how efficient coding can lower energy consumption, lowering carbon emissions while saving a lot of money. Participants from SE and EEE frequently concentrated on the economic side of sustainability whilst considering social issues. From a SE point of view, considering the environmental aspect of constructing data centres in their discipline is insignificant.

Though environmental issues are considered important and not entirely ignored, SE participants viewed these issues as irrelevant if they will have no involvement with constructing the data centre. Furthermore, data centres have become an essential part of society, and their positive aspects outweigh their negative aspects due to our dependency. SE students were trying to communicate how data centres could be more efficient in terms of operation and not construction.

SE students, as shown, did not prefer environmental studies because they preferred to focus on discipline-specific knowledge; Rampasso et al. (2019) noted how a lack of environmental studies might change students' perceptions. Pyrrhus claims that, because teaching SE students how to write effective programs is more crucial than teaching them about the environment, software engineering faculty do not offer a single environmental paper. Since students were required to learn about environmental studies in the sustainability paper, where other fields like CE and EE felt more at home, SE and EEE students may have felt alienated and lost.

Cybersecurity could be used as an additional example that SE students perceive to be more related to sustainability. In contrast, CE students could not see how it was related. The SE students believed a robust cybersecurity program would help protect the economy, society, and the environment (three pillars of sustainability). According to Pyrrhus, cybersecurity is a NFR in software engineering.

The SE participants in this study demonstrated the significance of NFR, and numerous studies in software engineering have corroborated this finding (Raturi et al., 2014; Penzenstadler et al., 2018; Naumann et al., 2015). Therefore, the data is consistent with the body of research that demonstrates that NFR are a critical concept in software engineering. Given that other disciplines have mentioned non-requirement concepts, it is possible to assume that other disciplines also have NFR. However, students and lecturers were unaware of such concepts in their respective disciplines.

Software engineers specifically selected Pyrrhus' paper on software methodology because, as mentioned earlier, it seemed relevant to sustainability. Pyrrhus' paper highlighted the significance of productivity and cost-cutting in software engineering. With the added benefit of connecting them to sustainability, all of the techniques and materials previously taught to students to save money can now be used in a more environmentally-conscious manner.

The data showed that the lack of transformation in participants is primarily due to how their transformation has already occurred in other discipline-specific papers. The missing transformation state can be described with the help of the study's model. Learners' journey through the liminality plane is only visible to them and not to the lecturer. This study confirmed students' transformation in discipline-specific papers, but suggested that the participants were not aware of this transformation, or became confused due to the lack of relevance in the sustainability paper. LCA being taught as an important tool in sustainability education does require that learners be able to comprehend the concept. The ability of CHE and ME students to cross the learning threshold in LCA through discipline-specific lessons is consistent with the model and literature, in which higher thinking, such as system thinking, is considered, not only a competency in sustainability, but also a threshold concept (Loringa, 2020).

In summary, this section focused on exploring threshold concepts in sustainability education and their perception by students from different disciplines. The findings suggest that students from different disciplines (e.g. Civil Engineering (CE), Chemical Engineering (CHE), Mechanical Engineering (ME), Electrical and Electronic Engineering (EEE), and Software Engineering (SE)) had varying experiences and perceptions of the sustainability material presented to them, with some finding it tedious or irrelevant to their discipline. All participants used system thinking to connect sustainability with their fields of study.

Certain disciplines, such as [CE](#), [CHE](#), and [ME](#), were less likely to use system thinking because the material was designed for their discipline and they were already familiar with the concepts. Other disciplines, particularly [EEE](#) and [SE](#), demonstrated higher cognitive and systemic thinking in an attempt to link sustainability to their disciplines. Both [EEE](#) and [SE](#) were concerned about non-functional requirements in their respective disciplines. Thus, sustainability does not have any transdisciplinary threshold concept; instead, threshold concepts are hidden in discipline-specific knowledge that are not explicit to students and lecturers.

Additionally, the study's model highlighted the importance of familiarity and relevance in helping students learn and comprehend sustainability concepts. This is why certain concepts, such as mass balance and system boundaries, were found to be more relevant to some disciplines than others. Students from certain disciplines (e.g. Software Engineering) tend to prioritize economic and technological aspects of sustainability over environmental ones.

The section that follows discusses students' perceptions of sustainability and sustainability papers. The section highlights how different disciplines have different understandings of sustainability and how this affects their learning.

5.5 Perceptions of Students in Sustainability: a Blessing and a Curse

As the title suggests, this section discusses how students' perceptions can have positive and negative consequences. In this study, participants' perceptions of the course and sustainability, in general, were directly related. In some ways, the feeling of alienation toward sustainability was caused by how the paper was designed and taught. This result is in line with the findings of [Palacin-Silva et al. \(2018\)](#) and [Nowotny et al. \(2018\)](#), who discussed how the course and the content affect students' perceptions. These findings indicate that the course structure, as well as the content, has a significant influence on students' perceptions (Figure 5.4).

I believe student perceptions are the primary reason that several disciplines have lost interest in sustainability (e.g., [EEE](#)). Chapter 4 shows how the majority of students were dissatisfied with the course and lost interest in it (primary [EEE](#) and [SE](#)). The majority of students thought sustainability was an abstract idea and didn't know how it could be used in their specific fields of study. This suggests that there needs to be a shift in the perception of sustainability in engineering education.

Personal perspectives, disciplines, and the sustainability paper were all interconnected for the students, which significantly affected their learning. This connection can be seen as a feedback loop in which the value students place on sustainability can be improved or diminished. For instance, how participants felt about sustainability in the course affected how they felt about sustainability in general. If the course is helpful, it will enable them to learn more; if it's harmful, the opposite will happen. A similar conclusion is reflected in the literature ([Tejedor et al., 2018](#); [McCormick et al., 2015](#); [Fisher and McAdams, 2015](#)).

5.5.1 Engineering Students' Perceptions of Sustainability

The field of engineering plays a crucial role in addressing the sustainability challenges that our society faces. However, different disciplines within engineering have different perspectives on what constitutes sustainable design and practice. This section aims to explore the views of various engineering disciplines on

Figure 5.4

Illustration of the participants' perceptions of sustainability and their views on sustainability papers

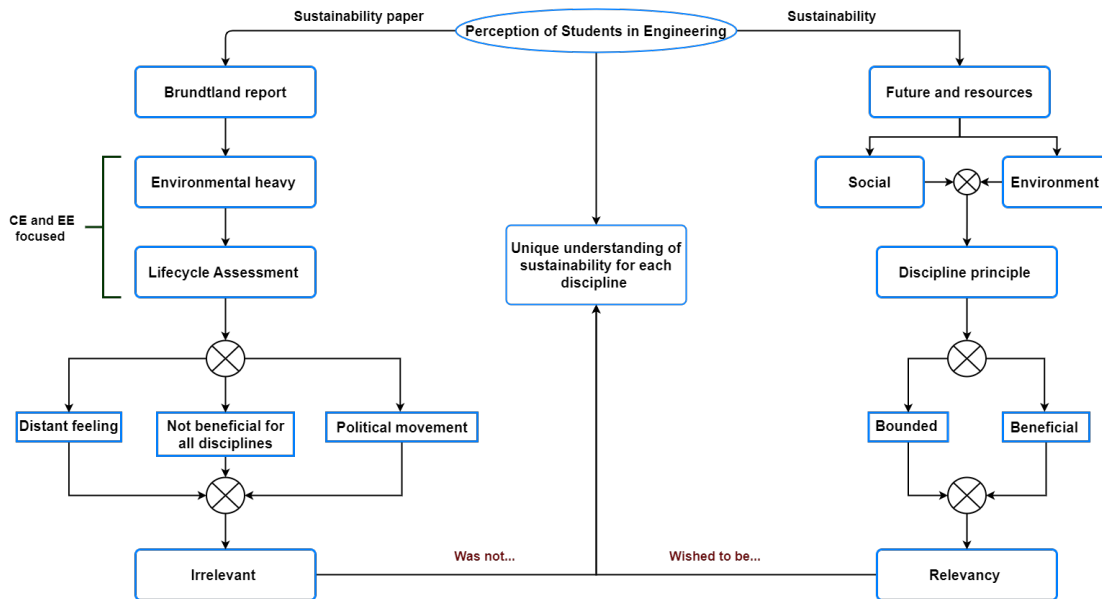


Figure note: This diagram summarizes the section and shows how participants hold different views on sustainability, what was taught, and what they expected to learn.

sustainability, and how these fields approach the concept. Through this examination, the section provides insights on how a more comprehensive understanding of sustainability can be integrated into engineering education and practice.

The disciplines of **CE** and **MPE** define sustainability as being closer to reusable and re-purposed materials, with a strong emphasis on environmental concerns. Surprisingly, none of these disciplines emphasised the use of better design or technology. Instead, they concentrate on the things their particular speciality can accomplish (i.e., bridges, roads, etc.).

It's concerning that an engineering student appears to be paying little attention to the importance of sustainable design. **Wilson et al. (2015)** also discovered that civil engineering students did not understand what sustainable design meant in their discipline; instead students of civil engineering recognised sustainable design only as the use of recycled materials, which holds true in this study as well.

The environmental impacts of poorly-designed products and services were identified by **EEE**, **SE**, **ME**, and **CHE** students as fundamental to a comprehension of

sustainability in engineering education. In their opinion, failing to design a viable product or service would ultimately result in the destruction of the environment. There is a distinction in how each discipline expresses “design” in this study. Each discipline’s point of view is explained, which clarifies different emphases in each discipline’s understanding of the term. However, the main distinction is linked to their discipline-specific knowledge.

In addition to design, durability and safety were given special attention by [EEE](#). Participants in [EEE](#) considered ESD-resistant circuit design⁸ and the incorporation of [RoHS](#) components into their bill of materials as examples of sustainable practises in [EEE](#). [Atlee and Kirchain \(2006\)](#) also found similar results, which further supports the discipline-specific aspect of sustainability.

[EEE](#) students emphasised reducing the need for product repairs and extending product life by implementing a better design so that ageing devices don’t need to be replaced. Interestingly, unlike other disciplines, [EEE](#) participants did not recognise power and renewable energy to be important in their disciplines. [Wilson et al. \(2015\)](#) also discovered the same mindset in [EEE](#), where participants did not consider power shortage a significant issue in substantiality.

Safety was another important characteristic for [EEE](#) students in sustainability. [Smith \(2009\)](#) confirms this finding by stating that the [EU](#) required the removal of hazardous materials from electronic products and the implementation of Extended Producer Responsibility, which requires electronic product manufacturers to take full responsibility for the product’s life cycle.

[ME](#) participants indicated that designing products without addressing sustainability is meaningless because the economy and purchasing power are tied to sustainable design. Participants used the economic component of sustainability to advocate for the importance of sustainable design. According to them, sustainable design will benefit, not just the economy, but also the environment. When considering sustainable design, social concerns were also taken into account. For example, [FE](#)⁹ recognised that employing fireproof materials in a building will assist, not just the environment, but also the social and economic pillars of sustainability ([Ramanujan et al., 2019](#)).

⁸Electrostatic discharge (ESD) is commonly known as “static electricity”. These discharges occur when an electric charge is built and transferred to another object, often accompanied by a visible spark. This can cause product defects or lead to unsafe circumstances.

⁹The [FE](#) discipline can be considered categorised as [ME](#), [EEE](#), and [CHE](#), per the suggestion of the participant.

Participants sought to connect sustainability to their respective fields' requirements; thus, each discipline took a different approach to sustainable design. Participant attempts to explain sustainability in their discipline, however, were sometimes met with confusion from others. SE participants' viewpoints were by far the most well thought out and developed. This was due to their familiarity with the discipline-specific knowledge that they had been introduced to previously.

SE participants focused on fundamental software methodology as the closest principle in sustainable engineering to their discipline. In a way, SE participants created a meaning for sustainability on their own, which helped them understand it better. Björnberg et al. (2015) and Zeegers and Clark (2014) encourage the idea of allowing students to define their own meaning of sustainability, and that is what SE students have done in this study.

SE participants agreed that the process of making software and the design of algorithms is akin to sustainable software development. The most common method for ensuring sustainability in SE is to create carefully thought-out software, taking into consideration every possible scenario that may arise over the product's lifespan. Becker et al. (2015) similarly hinted at efficient design in software engineering as being the aspect of the discipline most closely related to sustainability.

For SE participants, true sustainability was more closely related to the software life cycle side, from planning, development, and maintenance, to very minute things like efficiency and best designed algorithms. As a result, when given the opportunity, the SE group in the LCA assignment developed their own algorithms to minimise wait time and idle time.

Though energy efficiency is important, a programme may be made more efficient overall by employing approaches such as code re-usability, avoiding over-provisioning, and automated scaling. Software specialists mostly understand these terms; however, they may have different connotations in other fields. The significance of these terms for a SE in their area is sometimes overlooked by others.

However, these basic and sometimes overlooked notions have a significant influence on economic and environmental elements of sustainability. As the findings showed, auto-scaling is a programming technique used in data centres to

keep idle machines from being overworked. While this is a prevalent and even needed component in [SE](#), it is rarely considered in terms of its influence on the economic, social, and environmental pillars of sustainability.

[Naumann et al. \(2015\)](#) and [Hilty and Aebischer \(2015\)](#) similarly found the interconnectivity of software systems and the potential to consider how software products and services are more sustainable over their entire life cycle, primarily by reducing the energy and material flows they invoke and creating, enabling, and encouraging sustainable patterns of production and consumption through well-designed algorithms.

For example, Pyhruss explained the concept of auto-scaling, a way for companies to manage their computing resources more effectively. The idea is that, instead of having a set number of machines running all the time (for example, a million machines to satisfy everyone watching Netflix), the company can automatically turn machines on and off based on the system's current needs. This approach is more sustainable and helps the company save on resources.

Notably, efficiency in software engineering is not generally taught in relation to the environment, but rather in relation to how it might make more money for the company. Therefore [SE](#) students' training in [Software Engineering](#) specialised papers is more focused on economic factors.

Environmental aspects are mostly an afterthought or by-products of efficient codes and improved algorithms. Participants' perspectives, particularly those from [EEE](#) and [SE](#), emphasised economic elements that they believed were more important, not only in their profession, but also in their personal life.

This section discussed the perspectives of different disciplines within engineering on the concept of sustainability. It was found that the disciplines of [CE](#) and [MPE](#) focus more on reusable and repurposed materials and environmental concerns, but lack an emphasis on sustainable design or technology. Other disciplines such as [EEE](#), [SE](#), [ME](#), and [CHE](#) place more emphasis on poorly-designed products and services as important for a comprehensive understanding of sustainability in engineering education. Each discipline had a distinct emphasis on the term "design" and had a different focus on specific aspects of sustainability. Overall the study highlights that the understanding of sustainability in engineering education is discipline-specific, and there is a need for a more comprehensive approach.

The participants' perceptions are examined in the following section through the lenses of environment, economy, and society. The main pillars of sustainability are compared, and their significance in each discipline is discussed.

Environment, economy, and social aspects of sustainability in engineering

Analysing how students see the fundamental pillars of sustainability is also a valuable way to comprehend the perspectives of various disciplines on sustainability. The findings revealed a considerable gap between the value students place on the primary sustainability pillars in their respective disciplines, and the relevance of sustainability pillars in general.

CE and EE students regard the environmental aspect as the most significant component of their studies. Other disciplines shared the same perspective on economic challenges, but viewed economics as equally, but not more, critical than sustainability's environmental and social components. However, EEE and SE presented the highest percentage of respondents who determined economic aspects to be important.

Students were also asked how they perceived the sustainability triple bottom line without considering their disciplines, in order to show the importance they would put on each aspect of sustainability in general. The findings indicated a widespread awareness of social sustainability, as practically every discipline prioritises social concerns, almost as highly as environmental concerns.

The dramatic shift in how students evaluate the significance of social and economic pillars in general was an unexpected conclusion. Students from almost all disciplines personally view sustainability's economic and social components as being on par with the environmental aspects, which contrasts with how they view it inside their discipline. EEE and SE were the only disciplines in which the social and economic pillars were deemed more important.

The findings reveal that students' perceptions of sustainability in their disciplines, and in general, differ, and also that their opinions of sustainability in their disciplines differ entirely from their perceptions of general sustainability. While CE, EE, CHE, and ME deemed the environment significant, EEE and SE deemed

social issues to be of greater significance. The non-uniform distribution of significance placed on the sustainability pillars across disciplines, as noted by [McCormick et al. \(2015\)](#), might deter students from learning about sustainability.

What students have been taught in their respective disciplines directly impacts how they see the sustainability pillars. [Fisher and McAdams \(2015\)](#) mentioned that disciplines such as [CE](#), [EE](#), [ME](#), [CHE](#), and [MPE](#) show a stronger interest in the environment, since these disciplines have been exposed to more environmental science courses than [EEE](#) and [SE](#). Thus these students demonstrate a greater interest in the environmental elements of sustainability within their disciplines when questioned.

According to this study's results, most students considered social elements of sustainability to be as essential as environmental factors outside of their specialised disciplines. The findings of [Rampasso et al. \(2019\)](#) are consistent with this study's findings, which determined that environmental factors were the third most influential. In addition, [Dagiliūtė et al. \(2018\)](#) observed that engineering students place a greater emphasis on the social elements of sustainability.

Considering how each discipline understands the fundamental pillars of sustainability in general and in their specific disciplines, it is evident that the courses students have attended have influenced their perception of sustainability. Providing students with the opportunity to develop their definitions of sustainability within their different disciplines would aid in their comprehension of sustainability. [Zeegers and Clark \(2014\)](#) also confirm this finding.

Instead of overstuffing the sustainability curriculum with environmental studies that do not ultimately benefit students in specialised disciplines such as [EEE](#) and [SE](#), where they learn very little from it, the curriculum should focus on interdisciplinary topics. To overcome this imbalance, universities could consider re-designing their curricula. As sustainability is a difficult and undefined term, [Zeegers and Clark \(2014\)](#) recommend that students should be permitted to define it themselves. In light of this, [Zeegers and Clark \(2014\)](#) advocate a comprehensive overhaul of sustainability curricula. [Fisher and McAdams \(2015\)](#) likewise discuss the balanced curriculum design.

In summary, this section discussed the perspectives of various engineering disciplines on sustainability by analysing how students perceive the fundamental pillars of sustainability in their respective disciplines and in general. The study

found a significant gap between the value students place on the primary sustainability pillars in their respective disciplines and the relevance of sustainability pillars in general.

Students' perceptions of the importance of the triple bottom line of sustainability in their disciplines indicates the great importance of environmental and social pillars of sustainability, with most disciplines considering these two components equally critical.

However, when students were asked to consider the importance of sustainability without considering their disciplines, there was a shift in how they evaluated the significance of social and economic pillars, with students from almost all disciplines viewing these two components as being on par with the environmental aspects.

The study concluded that students' perceptions of sustainability in their disciplines and in general differ, and that their opinions of sustainability in their disciplines are completely different from their perceptions of general sustainability. This highlights the need for a more comprehensive approach to sustainability education and a greater emphasis on sustainability's social and economic aspects in engineering education.

5.5.2 Engineering Students' Perceptions of the Sustainability Paper

This section examines the participants' perceptions of the sustainability paper. Participants stated that the paper felt like a political movement and that the university did not appear to have put much effort into developing a suitable course that would benefit all disciplines. Findings show that students could not find any real connection to the paper and thus felt alienated from the course. These findings support Wilson's (2019) claim that students are more likely to ignore sustainability studies when they lack a sense of personal attachment and emotional connection to the course.

Fisher and McAdams (2015) also point out how important the students' perception is when designing a course. In this study, however, participants suggested that the course was merely another attempt to make university management

happy and appear sustainable in the eyes of the public. The sustainability paper failed to provide a positive and transformational experience for the majority of disciplines (e.g. [EEE](#) and [SE](#)). Sterling's (2011) proposal of incorporating transformational sustainability papers has proven to be successful in improving the quality of engineering education.

As [Sterling \(2011\)](#) suggests, teaching involves cognitive, intellectual, and affective dimensions. The emotional intelligence of students and how they interpret certain knowledge could therefore change their world-view and give them the ability to transform. This is an invaluable lesson for teachers, as the best way to reach their students and make a difference in their lives is to tap into their emotions and interests.

One aspect of the paper that seemed to pose challenges for most disciplines in this study was the heavy focus on the environmental aspects of sustainability. Disciplines such as [EE](#) and [CE](#) had no issue, unlike other disciplines. The heart of the problem is the way participants defined sustainability. Most participants held a similar understanding, mirroring the [UNESCO \(1987\)](#) report. There was clear evidence favouring environmental aspects of sustainability. The majority of disciplines (in particular [SE](#) and [EEE](#)) discovered parallels between the sustainability paper and environmental studies, indicating that it is more closely associated with fields such as [CE](#) and [EE](#).

This finding confirms [Rampasso et al.'s \(2019\)](#) observation that environmental studies are given higher priority in the curriculum, causing a misplacement of the importance on the other pillars of sustainability. This finding explains why [CE](#), [EE](#), [ME](#), and [CHE](#) prioritise environmental responsibility in previous sections because they have been educated to value environmental impacts.

That is why [EEE](#) and [SE](#) concluded that the paper on sustainability was largely irrelevant to them and that the notion of sustainability was vague. This result is interesting when compared with the literature. Many prior publications point out the excessive focus on environmental sustainability as a problem in engineering education ([Björnberg et al., 2015](#); [Guerra, 2017](#); [Zhou et al., 2013](#); [Rampasso et al., 2019](#); [Mulder, 2017](#)).

The apparent primary disconnect for [EEE](#) and [SE](#) in this study was caused by their [LCA](#) assignment. The data indicated that the [LCA](#) assignment appeared to have been written with [CE](#) and [EE](#) in mind. Participants from other disciplines felt

alienated from the course when they couldn't find any concepts pertinent to their fields. This point is evident in students' project selection preferences, as shown in Figure 4.4, where students hoped to make use of their skills by selecting "E-vehicle" as their assignment. These findings suggest that, rather than forcing a one-size-fits-all approach, a course's design should be customised to the unique needs and goals of the learners. Aginako and Guraya (2021) also noted this issue that the number of environmental courses is usually higher than those focused on the social and economic pillars in higher education.

Wilson et al. (2015) confirms that students perceive sustainability with their disciplinary mindset, and if they are not met with proper task-related assignments to their disciplines, students will feel alienated. EEE and SE students, for example, did not bother attending lectures and were content with merely passing grades. Additionally, SE students noted that the course had nothing to do with SE studies. Pyrrhus also expressed his unhappiness with how the course was structured and administered, especially for SE students.

Pyrrhus was concerned that many of the projects assigned to students were unrelated to software engineering, causing them to miss out on key software development principles. The contents, in his opinion, should have been shared across all disciplines, but he knew this was impossible given how the managers operate. In his opinion, the lack of relevance to software disciplines in the sustainability course was the leading cause of the alienated feeling that most students felt. As a result, students already feeling overwhelmed with their course load were further discouraged to find that the sustainability class was not teaching them any new material or giving them an opportunity to increase their technical knowledge.

Most of the criticism was directed at the course's lack of relevant concepts to each discipline. From this standpoint, lack of relevance can be considered one reason why most students found LCA to be troublesome. Since resource management and environmental implications are central to CE and EE, the paper seemed to place more emphasis on these areas. Alternatively, it could simply mean that a lack of familiarity and relevance of content derived from how the paper was taught by CE lecturers, such that resource management and environmental implications were bounded within their discipline (Section 5.4).

As a result, SE and EEE had to adapt to an alienated knowledge far from their comfort zone. The study model may be used to describe the alienated feeling generated by placing students in the far left area of liminal space, where the concepts covered have little significance, and it takes considerable work for students to make sense of the course content. As per Wilson et al.'s (2015) observation, this caused students to not engage with the content and stopped them from genuinely learning about sustainability.

Students in their final year who are focused mainly on their discipline-specific papers would not bother learning a new concept that has no relevance to them. To that end, different disciplines developed a unique understanding of sustainability. Fisher and McAdams (2015) discovered similar results where students' views of sustainability were influenced by the type of course they took. According to the findings of this study, students' perceptions of sustainability and the course significantly impact their learning experiences and how sustainability is perceived, which is consistent with Fisher and McAdams' (2015) findings.

Furthermore, as in Wilson's (2019) research, participants in this study perceived sustainability differently depending on their disciplines. As previously demonstrated, different disciplines favour different sustainability-related topics within their disciplines (e.g., SE found cybersecurity necessary, while CE found it least related). CE and EE were the only disciplines that considered the paper informative, and even they did not learn much about sustainability. Figure 4.9 depicts how the vast majority of participants are unsure whether they have learned anything useful.

5.5.3 Conclusion

The personal perspective of participants on sustainability was heavily influenced by their discipline. According to the data, the same disciplines that deemed sustainability essential in their disciplines would place a greater or equivalent value on it in their personal life (Figure 4.5). CE, EE, ME, and CHE are examples of these disciplines. That does not mean that students from other disciplines who found sustainability unrelated in their discipline would not care about it in their personal life; EEE and SE students, for example, considered sustainability to be more important in their personal lives than in their disciplines.

The participants' perceptions of sustainability and the way that their discipline-specific conceptions substantially influence these perceptions, demonstrate that the model representation is valid. The key point to remember here is that the sustainability threshold that students needed to pass had previously been met in another paper, and as the model shows, there was so little relevant content in the sustainability paper that **EEE** and **SE** students were unable to improve their learning experience. Students felt disconnected from the class as a result of this lack of relevance, and they quickly lose interest. That is why the majority of the **EEE** and **SE** students were unsure whether they had learned anything from the course. Clearly, participants' ability to connect sustainability to their field, as well as their discontent with the paper, shows that threshold concepts for engineers are nested inside their disciplines, in contrast to **CE** and **EE**, where the majority of students were satisfied and claimed that they had grasped the subject.

5.6 Chapter Summary

This section described, explained, and exemplified several main themes found in Chapter 4. According to the data, there are no overarching threshold concepts in sustainability engineering. This study's findings show that all threshold concepts in sustainability are hidden within disciplines. Within each discipline, some concepts can be identified as threshold concepts for disciplines and sustainability. By studying these threshold concepts, students can gain a greater understanding of the material and better understand how sustainability principles can be applied in different contexts.

LCA as a means of engaging students in sustainability education was also discussed. It was recommended that **LCA** needs to be incorporated into first-year curricula to serve as a threshold concept, while **LCA** for fourth-year students needs to be highly project-oriented and related to their disciplines to have a meaningful impact on the students. Therefore, it is essential for educators to identify and consider the key threshold concepts within their disciplines in order to ensure that students are engaged with sustainability learning.

Finally, students' perceptions of sustainability and the sustainability paper were evaluated, and the discussion revealed that most students have little understanding of sustainability. Furthermore, it was discussed that the lack of discipline-related concepts in the sustainability paper gave most students a negative feeling. In order to properly integrate sustainability learning into students' higher education, educators need to create curricula that take into account the key threshold concepts within their disciplines and promote meaningful engagement with sustainable practices through project-oriented activities.

The following chapter presents and discusses a review of the research questions' answers and conclusions, implications for theory and practice, suggestions for future research, and the study's strengths and limitations.

Chapter 6

Conclusion

6.1 Chapter Overview

This chapter aims to provide a comprehensive overview of the research questions discussed in the previous chapter, along with their implications, strengths, weaknesses, and future research possibilities. The chapter has been divided into four sections. Firstly, a summary of the research questions will be presented, followed by the conclusions drawn from the previous chapter. Next, the study's implications will be discussed, highlighting their significance within the field. Additionally, the strengths and weaknesses of the research design will be explored to provide a balanced perspective. Finally, possibilities for future research will be suggested to facilitate further exploration of the topic.

6.2 Unlocking the Answers: Concluding Statement

This section provides direct answers to the research questions by summarising the major themes discussed in Chapter 5. The main goal of this section is to provide a brief summary of the main points discussed in order to answer all of the research questions and provide a conclusion to the study.

This section answers the following research questions in the order of support questions first, followed by the main question.

Main question: How do student perspectives on sustainability influence students' understanding of threshold concepts in sustainability engineering education?

Supporting question:

- What are the threshold concepts in sustainability for engineering disciplines?
- Are threshold concepts in sustainable engineering common across disciplines?
- How do students perceive sustainability?

What are the threshold concepts in sustainability for engineering disciplines?

It was challenging to pinpoint the threshold concepts in this study. The existence of actual threshold concepts in sustainability remains uncertain, and a comprehensive analysis of every engineering discipline is necessary to address this question. Distinguishing a genuine threshold concept in sustainability is complicated, and several researchers have encountered difficulties in defining sustainability in engineering (Loringa, 2020; Scott, 2012). This study discovered a link between disciplines and sustainability, where threshold concepts are contextualised among discipline-specific notions.

The realisation was primarily the result of observing SE students, who described how the sustainability course was unrelated to their discipline, and they nominated Pyrrhus' paper on advanced software methodology as being akin to sustainability in their discipline. Through their interviews, SE students were able to explain how the software methodology paper, not only provided them with an understanding of the concept of sustainability, but also opened up the possibility of using sustainable approaches in their engineering discipline. As a result, this study not only demonstrates that the concept of sustainability is embedded within discipline-specific notions, but it also demonstrates how these same concepts can be used to bridge the gap between engineering and sustainability.

According to the data, SE students considered Non-functional Requirement (NFR) to be threshold concepts in their discipline. Pyrrhus emphasised this further by proposing NFR as a viable threshold concept in sustainability. His assessment was supported by literature, which treats software engineering as a new discipline that must be approached differently than the other disciplines (Naumann et al., 2015; Hilty and Aebischer, 2015; Raturi et al., 2014). Pyrrhus suggested that software engineering and sustainability can be approached holistically through the concept of NFR, which are used to bridge the gap between SE discipline and sustainability.

The concept of “cybersecurity” is another example that supports this finding. SE students found cybersecurity to have a direct link to sustainability in their disciplines, whereas CE and EE participants found no link. SE students saw confidentiality and cybersecurity as a way to ensure the protection of the environment and its resources, whereas CE and EE students viewed it as a technical issue. From a technical standpoint, CE and EE students saw cybersecurity as a way to protect against malicious attacks and keep information secure, while SE students found that cybersecurity is a way to maintain sustainable practices in the environment, which is why it is seen as an important part of their discipline.

According to Pyrrhus, cybersecurity is considered a NFR in software engineering. This means that NFR is a crucial concept for both software engineering and the integration of sustainability into the discipline. This is an important insight because it implies a connection between software engineering and sustainability that is often overlooked in sustainability education. Specifically, software engineering principles such as security and reliability can significantly promote a software product’s sustainability, including its algorithms and codes.

Other fields showed similar patterns when it came to discipline-specific ideas that could fill the gap in engineers’ sustainability education. ME, EEE, and CE participants have all identified some distinct approaches to incorporating sustainability into their respective disciplines. EEE, for example, identifies “design” as a key area for integrating sustainability into the curriculum.

As discussed in Chapter 4, EEE participants’ understanding of their curriculum leads them to believe that they can help protect the environment by designing efficient circuit boards. The same finding was evident among SE students, who used “algorithms” to achieve an environmentally friendly solution in their report

as discussed in their focus group. Meanwhile, CE participants identified reusing and recycling materials to build infrastructure as a critical component for achieving a sustainable outcome.

In all these cases, the participants were able to identify ways to incorporate sustainability into their respective curricula, demonstrating that relevant content is required to teach engineering students about sustainability. Relevance can thus foster a close, interconnected feeling among students in their disciplines, where their perception can inform their learning ability (Wilson, 2019). This demonstrates that, when students are encouraged to investigate ways to incorporate sustainability into their current curricula, they become more engaged and involved in the process.

The literature about sustainability and threshold concepts is not specific to any particular field of study but provides a general understanding of sustainability. Engineering students can gain a deeper understanding of sustainability by grasping the systems approach to problem-solving, recognizing the interdependence of social, economic, and environmental factors, and applying life cycle thinking to the design and assessment of engineered systems and products, which are all considered threshold concepts in sustainability (Loringa, 2020). It is important to teach these concepts within their respective disciplines and ensure they align with students' learning throughout their academic journey. Otherwise, even though these concepts may be considered threshold concepts, they will not be helpful to students as they will not relate to their understanding of the world.

Even though these concepts were covered in the sustainability paper, they were taught through the lenses of other disciplines such as CE and EE, thus not giving students the opportunity to see how sustainability is relevant to their field (Fisher and McAdams, 2015). Therefore, the participants in this study have a distorted understanding of true sustainability through the lenses of other disciplines such as CE and EE, thus not allowing students to see how sustainability is relevant to their field. This lack of understanding can have serious consequences in the long term, as students may not be able to recognise or realise the importance of sustainable practices when they enter their chosen field (Wiek et al., 2011).

As a result, the value of sustainability was lost on them, affecting their understanding and skills. The Head, Hands, and Heart learning objective demonstrates how this is detrimental to students' understanding of responsibility. Students' cognitive (head) and psychomotor (hands) understandings of sustainability were not aligned because their emotion (heart) was not optimal for learning about the concept. Without the proper emotional foundation, students may not develop a holistic understanding of sustainable practices and thus miss out on an important facet of their education (Sipos et al., 2008).

For example, disciplines such as EEE and SE partially ignored environmental aspects in favour of economics because they were reluctant to match their learning to CE and EE. This indicates the need for proper reform in emotional education to accompany intellectual and practical training, as suggested by the Head, Hands, and Heart learning objective.

The CE and EE states of learning were not even better because they all ignored design and requirement needs in favour of environmental protection. The absence of balance presented here is not new and has been discussed by a number of researchers (Wilson et al., 2015; Fisher and McAdams, 2015; Tejedor et al., 2018; McCormick et al., 2015). However, most literature in this field ignores the emotional connection aspect of the curriculum and, in turn, favours the neo-liberal model. This study highlighted the area where educators need to focus if they are in search of transformation, as they all suggest: focusing on disciplines instead of broad sustainability concepts that are ever-changing and different depending on the geographical place. As a result, a lack of balance in education has become more evident, prompting researchers to focus on the emotional connections and curricular elements necessary for effective teaching and learning.

Simply put, sustainability is a complex and wide-ranging topic encompassing various disciplines, cultures, religions, customers, and geographical locations. As a result, there are no specific threshold concepts in sustainability, as this study suggested. Therefore, engineering educators should focus on discipline-specific concepts that serve as the building blocks of their fields. This approach can help students become better engineers and equip them with the skills needed to tackle the constantly evolving challenges of sustainability.

If engineering disciplines are taught solely through the lens of CE and EE disciplines, it can cause more harm than good. This approach can alienate students from sustainability and make it difficult for them to connect with the relevant interconnectedness of their disciplines. Graduating without a solid understanding of sustainability and discipline-specific concepts can leave students feeling stuck in a liminal space. Therefore, it is crucial to prioritise discipline-specific concepts while emphasising sustainability's importance.

Are threshold concepts in sustainable engineering common across disciplines?

Simply put, the answer is no. While there are no widely recognized threshold concepts, certain shared concepts could be considered threshold concepts if they were tailored to meet the specific requirements of a particular discipline. The threshold concepts in this study are divided into two categories: generic and discipline-specific concepts. While generic concepts are broad and could be applicable to many fields of study, discipline-specific concepts are more tailored to a specific field and its unique knowledge. Both generic and discipline-specific concepts play an essential role in the knowledge construction process, as they provide the learner with a clear understanding of the structure of a field and serve as guiding principles for further learning.

Although the generic concepts are generally thought to be shared across engineering disciplines, the specific application and implementation of these concepts may differ depending on the engineering field. A threshold concept, such as the systems approach to problem-solving, applies to all engineering disciplines, but how it is applied varies depending on the system being studied (Loringa, 2020). Similarly, life cycle thinking is a fundamental concept that can be applied to all engineered systems and products; however, the exact methods and tools used to assess a product's impact on the environment and society vary depending on the field of engineering (Penzenstadler et al., 2015).

The findings of this study, for example, show that SE students' perceptions of LCA differ greatly from CE students' perceptions of LCA. While the ultimate goal of both disciplines is to protect the environment, they approach it in very different ways. In their project, SE students included a brief section in which they

applied their knowledge of advanced software methodology to develop an algorithm that reduces car idle time at traffic lights. On the other hand, CE students take a more traditional approach to environmental protection; in their discipline, they are in charge of building the aforementioned traffic light.

That is why, in this study, it was highlighted that threshold concepts are hidden within disciplines and why the paper, as discussed in Section 5.5, was received poorly by a majority of disciplines where their disciplinary knowledge was not met, but ignored in favour of a more common understanding of LCA. To effectively bridge the gap between SE and CE students, making them aware of each other's discipline requirements is essential.

On the other hand, discipline-specific concepts provide a more detailed understanding of the field and help hone the learner's understanding of engineering principles and techniques within their domain with a heavy emphasis on sustainability. Such concepts are usually taught at a more advanced level. They require a greater depth of knowledge, making them essential to the engineer's ability to design, build, and sustainably manage complex systems.

For instance, the structural analysis in civil engineering provides the foundation for understanding how to build safe and sustainable infrastructure. Algorithms in software engineering help students learn the fundamentals of writing efficient code. Similarly, in electrical engineering, courses such as circuit analysis provide the necessary knowledge to build circuits and systems that are both energy-efficient and reliable.

How do students perceive sustainability?

The perception of sustainability among students can vary depending on a number of factors, including their prior knowledge and experiences, their cultural and societal background, and the specific context in which they are learning about sustainability. Furthermore, the approaches used to teach sustainability can have an impact on how students perceive the concept.

According to the data, the context has a greater influence on students' perceptions. In the context of learning, it is evident that students' understanding of sustainability increases when they are presented with meaningful experiences and

opportunities to interact with their discipline-specific knowledge. Students' attitudes and values around sustainability are shaped by the level of engagement they have with their discipline-specific concepts and the instructor's discipline.

Therefore, in order to promote a better understanding of sustainability among students, instructors should focus on providing meaningful experiences that involve discipline-specific content related to the students' disciplines. This could include providing real-world examples of how the discipline is connected to sustainability and how it can address global challenges.

In this study, however, the real-world example did not include discipline-specific content. That is why students perceive sustainability as a broad and complex concept encompassing many social, economic, and environmental issues. While it is true that sustainability is broad, this method was not suitable for students who were in their last years of study. The lack of discipline-specific content made it difficult for students, especially those in their final years, to understand the concept of sustainability more meaningfully.

Others had a more narrow view of sustainability, focusing primarily on environmental issues such as reducing carbon emissions or protecting natural resources. They had difficulty understanding the connections between environmental, social, and economic issues. This lack of understanding had a negative effect on the student's overall perception of sustainability among the students.

It was difficult for students in their final years of study to fully grasp the need for studying a generic course on sustainability, and thus their perception was altered, and, in some cases, they developed a dislike for the course and sustainability. This was primarily due to the course, which provided a very general overview of sustainability without delving deeper into any specific topics or providing an in-depth understanding of the field.

It is important to note that students' perceptions of sustainability can change throughout their education and experience as they are exposed to different perspectives and learn more about the concept's complexity. The findings showed that first-year students had a much more open mind toward sustainability and were more engaged in learning about it.

Therefore, it is important to create an inclusive and interdisciplinary learning environment that encourages the exploration of different perspectives and promotes critical thinking about sustainability. As the study suggested, this could be done through more detailed and specific courses on sustainability that provide students with opportunities to engage with their discipline's material in a meaningful way.

How does perspective in sustainability influence understanding of threshold concepts in sustainability engineering education?

This study's [findings](#) on the connection between sustainability education and students' perceptions support the idea that the two are tightly intertwined. This finding has been highlighted by demonstrating how the timing of [LCA](#)'s introduction could affect the extent to which the students view it as a paradoxical concept (Section [5.3](#)). Additionally, concepts previously thought to be a niche for engineering disciplines were found to have a stronger link to sustainability (Section [5.4](#)). This research also proposed a revised model of [TCT](#) and [liminality](#), an improvement on the original liminality model (Figure [2.3](#)) that facilitated better comprehension of students' perception (Section [5.2](#)) and can be used to interpret their feelings more easily.

Suppose students in liminal space do not have a well-developed understanding of sustainability. In that case, the model predicts that they will have a more challenging time moving through the transformation intended for sustainability education. In light of the findings, it would appear that all students began the course with a similar level of openness to the most frequently covered concepts in sustainability education (i.e. [LCA](#)). While some of the group found [LCA](#) to be very useful, others disregarded it as unimportant. It was evident by the end of the data analysis that most students' perspectives on [LCA](#) and other topics had been significantly shifted. Perspective differences were ultimately identified as the root of the problem for such divergent levels of acceptance ¹.

The paradoxical nature of the [LCA](#) found in this study demonstrates an emotional connection which influenced participants' learning experience. Depending on when students are introduced to [LCA](#), it could be a possible [TCT](#) (Section

¹Refer to [Findings Chapter](#) and [LCA as a paradoxical concept](#) in the discussion chapter for more information

5.3) - or not. A more thorough examination of the data reveals that the students' empathetic connections account for how LCA was perceived. The participants had no trouble carrying out the LCA procedure (i.e. not challenging), and none of the cohort (i.e., junior and senior engineers) had trouble comprehending the LCA methodology. However, junior engineers' emotional attachment to the idea helped them understand how transformational LCA was. In contrast, senior engineers could not find any connection and, in return, developed an alienated feeling toward sustainability. Having said that, not all disciplines had a poor opinion of LCA. For instance, neither civil nor environmental engineers displayed any signs of opposition to the LCA or sustainability course. However, their understanding of sustainability is open to the possibility of being misconstrued.²

Civil engineers viewed sustainable development as purely an ecological concept where their knowledge could be applied to reduce material waste. In comparison, participants in other disciplines saw sustainability primarily as a tool for streamlining inefficient processes. Due to the enormous variety of disciplines and the various viewpoints they displayed, it is impossible to precisely identify the inefficiencies. Software engineers, for instance, see inefficiency as a high operating expense (Figure 4.8). Therefore, if they could reduce their costs by improving their designs, it would eventually lead to a more environmentally friendly design (system thinking). Although the software and electrical engineers prioritise economic and social sustainability more than environmental sustainability, this does not imply that they are unconcerned with the latter.

Software and electrical engineers' capacity for system thinking has altered their ability to view sustainability in their fields from a specialized perspective. The difference in perspective between software and civil engineers created a hollow feeling where neither discipline could connect with another niche concept of sustainability in their disciplines. Concepts which seemed practical to software engineers were regarded as irrelevant to civil engineers (i.e. cybersecurity). However, software and electrical engineers' points of view were ignored, since the course was offered from the standpoint of civil and environmental engineers.

The study's model revealed that learners would not be able to advance past the liminality stage if the concepts were unrelated to their discipline. Irrelevant concepts would create an alienated feeling that affected students' perceptions of sustainability and impacted what they could comprehend. This idea is

²See section 5.5 for more information.

supported by the software engineers, who showed they could pass the threshold with the help of their discipline-specific papers. Although they had a negative view of sustainability, they could at least combine sustainability notions with discipline-specific concepts to produce a novel educational experience (i.e. [NFR](#)). Regrettably, this cannot be stated for the remaining disciplines. For instance, since they were never able to learn about sustainability through their field-specific papers, electrical and electronics engineers could not demonstrate any transformative moments. The transformation sought in sustainability education, and that literature hopes can be implemented, is not something that is currently available. The transformation relies on each individual's perception and understanding of the world. The student's own experience should be paramount when it comes to sustainability education. Universities should seek to inspire students to achieve their discipline goals with sustainability in mind, instead of shaping the discipline according to sustainability goals.

The students' struggle to navigate liminal space was apparent for disciplines where they failed to find any value in sustainability. Further analysis indicated that their discipline goals and sustainability goals conflicted. In other words, their transformation never happened, and it denied their chance to find a relevant concept to anchor on, so they could dig themselves out of the liminal space.

According to the participants' perceptions in this study, they have developed a consistent and routine learning style in accordance with their disciplines. The preferred way of thinking, processing, and understanding information is the learning style. That is why they feel alienated when the information provided does not meet the expectations of their discipline and requires them to accommodate the learning style of another discipline. The subjective nature of learning styles further prevents learners from accepting different information. Each learner will have an understanding of the world, making it difficult for teachers to provide effective instruction.

This result is consistent with the idea presented in *Heads, Hands, and Hearts Competencies* that a learner and their environment cannot be perceived in isolation from one another or in a binary fashion ([Sipos et al., 2008](#)). What this means is that the learner's actions, mental processes, interactions, behaviours, intentions, emotions, and attitudes are all embedded in the context of the world to which the learner belongs. A body, which has a physical presence and lives

through experience, and an active consciousness, or “reaching out” mind, are required for all of our real-world experiences ([Papadopoulou and Birch, 2013](#)).

De Haan’s ([2006](#)) introduction of *Gestaltungskompetenz* competencies to aid in sustainability education includes a number of characteristics that necessitate changing perception. [Table 2.2](#) lists all of the competencies, and as can be seen, the majority of them necessitate understanding the problem from a different perspective. Even competencies requiring system thinking and planning would fail if students were alienated from the concept of sustainability. Consequently, to successfully achieve a sustainable future, an understanding of the competencies should be accompanied by a change in perception about sustainability, which this study helped to develop.

[Sterling and Thomas \(2006\)](#) also provided a comprehensive list of sustainability competencies. Their work has been used to create course materials that make students feel more included ([Dyer, 1996](#); [Wood et al., 2016](#)). Some of the most important characteristics in [Sterling and Thomas’s \(2006\)](#) work are knowledge, value, skills, and understanding. Students must understand how their disciplines contribute to a more sustainable future. They will begin to understand and apply critical thinking to their design once they are aware of its value. Thus, students will develop more related skills within their specialised fields.

In short, perception is very important when it comes to identifying threshold concepts in sustainability. Sustainability is a very vague and confusing term that is very hard to define. As a result, providing students with adequate instruction and resources to help them understand the implications of sustainability is essential in order for them to understand the importance of its application. This study showed that each discipline has a different understanding of sustainability. Therefore, it is important to understand the perceptions of each discipline in order to be able to effectively teach and identify threshold concepts.

The next section will provide the main implications and recommendations for educators and researchers in the field of threshold concept theory.

6.3 Implications and Recommendations

This study aimed to identify threshold concepts in sustainability for engineering students. The findings of this study have contributed to the understanding that, contrary to what one might expect from a common list of concepts in literature, there are no overarching threshold concepts in sustainability. Given that sustainability is a highly complex and multi-dimensional concept with multiple interpretations depending on the individual and their context, the threshold concepts are hidden within engineering disciplines.

The data showed that certain discipline-specific concepts that are unique to engineering disciplines have more in common with sustainability than expected. These concepts are usually taught within each discipline, and they are unique only to them. However, these concepts could be used to train engineers to be more sustainable. This means the potential for senior engineering students to develop an understanding of the value and importance of sustainability in their fields is dependent on discipline-bound concepts.

The findings helped develop a new model for liminality in threshold concept theory. A model was developed to help understand the gap in the existing liminality model. The new model can clearly define the learner's status and identify the position in which the learner seems to see themselves in relation to the concepts in the paper. This model not only helps to define the level of understanding learners have of the concept, but also illustrates how different interpretations can be formed depending on the individual's context. The new model of liminality not only provides an in-depth insight into the learner's position and understanding, but also provides a more holistic view of their journey and how they could be better supported through their learning process.

The study points out that students have different understandings and expectations, according to their disciplines, when it comes to sustainability education. This has significant implications for educators, suggesting that a one-size-fits-all approach to sustainability education is ineffective. Students must feel included in the paper; otherwise, they will not be able to transform their perceptions.

Another important implication of the study derives from findings made when introducing [LCA](#) to engineering students. While all disciplines found [LCA](#) to be

important, only junior engineers found it transformative. Senior engineers found it tedious and time-consuming. The study demonstrates that, if senior students are able to feel included in the learning process and recognise the value of their disciplines in [LCA](#), they can have a transformative experience. This transformation however means a discipline-related project.

Students' perceptions have a strong influence on their learning. Data showed that students who found the paper less relevant to their discipline had less enthusiasm to learn, and in most cases, they stopped attending the lectures and hoped to get a pass instead. The students' perception was interlinked to discipline-bounded concepts used in the sustainability paper. Sustainability concepts that were more relevant to students' disciplines were associated with more positive student perception, and thus better understanding.

Data showed that different emphases on the sustainability triple bottom line changed the students' perceptions of sustainability. For disciplines such as [SE](#) and [EEE](#), whose core design is to help with economic aspects, they expect sustainability to be more relevant to the economic pillar.

The sustainability course should not be designed to fit all engineers. If students are to be open to learning about sustainability, each discipline has different needs that must be met. Therefore, the course must be designed to accommodate each engineering discipline's needs.

6.4 Strengths and Limitations of the Study

The study's research design has strong and weak points, as do the designs of most other studies. The study looked at how students thought about sustainability and key concepts in sustainability. One of the study's strengths was that it used multiple research methods to guide the investigation and shed light on the complicated research questions.

An in-depth and reliable assessment of threshold concepts within engineering education has been uncovered through an embedded design with a qualitative and quantitative methodology ([Creswell and Clark, 2017](#); [Punch and Oancea, 2014](#)). Using qualitative and quantitative methods, the study was able to look at how students understood sustainability and its key ideas from different points

of view. Data collection enabled an in-depth study of students' perceptions of sustainability by asking questions in formal and informal interviews and collecting questionnaire responses (Gray, 2017; Cohen et al., 2017). Group interviews yielded rich data because they engaged participants, who were not used to describing their practices, in fruitful discussions that clarified their professed values and norms (Morgan, 1996).

The utilisation of phenomography is another strength of this study. Understanding each participant's point of view in relation to their disciplines was made possible by phenomography. This study's combination of phenomenography and larger sample size with a collective viewpoint, rather than depending exclusively on individual perspectives, allows for a thorough knowledge of the collective viewpoint's lived experience.

The main limitation of this study was that it focused on all engineering disciplines rather than just one. As a result, because the participants from any given discipline were few in number, the results of this study were inconclusive in some ways, and the results may not be representative of what is seen in larger studies. More in-depth research into each area of engineering could lead to a better understanding of how certain areas of engineering work together.

Another limitation in this study was the lack of a consistent number of participants for each discipline. This resulted in some disciplines having fewer participants than others, which could potentially affect the accuracy of the data collected. A bigger sample size would have generated a wider range of data that would have made the overall results more valid and reliable. Although this study has provided a fascinating insight into engineering disciplines and sustainability, further research should be conducted to gain a more in-depth understanding of threshold concepts for specific disciplines.

Another major limitation that contributed to the inconsistent participant numbers in this study is COVID-19. The original design, prior to lockdown, considered focusing heavily on quantitative results from a survey from two universities in Australia and New Zealand. However, the number of respondents for the survey was so limited that it was not used. This greatly impacted the results of the study, as the analysis was unable to reflect the opinions of a larger group of students from all over Australia and New Zealand.

6.5 Suggestions for Further Research

The drawbacks of the current study need to be addressed in further research. Firstly, with the current understanding that threshold concepts are discipline-bound, focusing on each discipline separately is recommended, rather than studying all disciplines at once. Focusing on a single discipline would allow for a more detailed exploration of the specific threshold concepts that appear in each area, and give a greater opportunity to gain insights into how these concepts are learned and applied.

Second, I would recommend focusing on the psychology of learning and how it connects learners' perceptions to their disciplines. By exploring the psychological aspects of learning, researchers can gain further insight into the motivations of learners and the context in which threshold concepts are applied.

Finally, it is without a doubt that this study has created a stepping stone for further research, especially with the introduction of study models that look at the liminality stage in threshold concept theory. It is, therefore, necessary to continue exploring threshold concept theory with the help of the model to provide an even better understanding of how knowledge is learned and applied in sustainability education.

6.6 Concluding Comment

This study is believed to be the first to examine students' perceptions in order to identify threshold concepts in sustainability. My personal experience in sustainability inspired this research, and the threshold concept theory was the perfect framework to use to understand the missing links existing within engineering education. Through this research, I hope to contribute to the current literature on sustainability and bridge the gap between traditional engineering and sustainable engineering.

The findings indicated that threshold concepts for sustainability in engineering are discipline-bound. Each discipline in this study showed how students are most comfortable with concepts that are nested within their disciplines. One

primary concern highlighted in this study was the lack of connectedness of sustainability papers to most engineering disciplines. It was discussed that the courses are taught in ways that have no real connection to some disciplines. The results of this research suggest that it is essential to ensure that there is a meaningful relationship between disciplines when discussing the concept of sustainability.

The insights provided in this study can be used to design a course that has the ability to transform students' perceptions of sustainability in relation to their disciplines. The model developed in this study provides a greater opportunity to conduct more research, not only in sustainability, but also in the field of threshold concepts. By integrating the concepts of sustainability with other disciplines, this model can help develop a holistic and meaningful understanding of sustainability in the context of the courses being taught.

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Appendices

Phase 1 FEDU Ethics Acceptance Letter

Te Kura Toi Tangata
Faculty of Education
The University of Waikato
Private Bag 3105
Hamilton, New Zealand, 3240

FEDU Ethics Committee
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

24/4/2019

Dear Sina Enteshari

FEDU Ethics Application Approved FEDU022/19

I am pleased to advise you that your ethics application for the project entitled “Teaching Sustainability to Engineering Students in the Light of Threshold Concept Theory” was approved by Te Kura Toi Tangata Faculty of Education Ethics Committee on April 24th, 2019.

Please be aware that the Te Kura Toi Tangata FEDU Ethics Committee must be advised (by memo) of any changes to the details recorded in your ethics application. Please send any such advice to fedu.ethics@waikato.ac.nz. You will receive a memo of approval once the change(s) has been considered.

Kind regards

Co-chair

Te Kura Toi Tangata Faculty of Education Ethics Committee

Phase 2 FEDU Ethics Acceptance Letter

Te Kura Toi Tangata
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

11/5/2020

Dear Sina Enteshari

Division of Education Ethics Application Approved FEDU027/20

I am pleased to advise you that your ethics application for the project entitled “Teaching Sustainability to Engineering Students in the Light of Threshold Concept Theory” was approved by Te Kura Toi Tangata Division of Education Ethics Committee on May 11th, 2020.

Please be aware that the Te Kura Toi Tangata Division of Education Ethics Committee must be advised (by memo) of any changes to the details recorded in your ethics application. Please send any such advice to fedu.ethics@waikato.ac.nz. You will receive a memo of approval once the change(s) has been considered.

Kind regards

A handwritten signature in black ink, appearing to be 'M. Smith'.

A handwritten signature in black ink, appearing to be 'R. Smith'.

Co-chair

Te Kura Toi Tangata Division of Education Ethics Committee

Phase 2 Ethics External Approval Letter



THE UNIVERSITY OF
**WESTERN
AUSTRALIA**

Human Ethics

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Our Ref: RA/4/20/6216

18 May 2020

Dr Sally Male
School of Engineering
MBDP: M018

Dear Doctor Male

HUMAN RESEARCH ETHICS OFFICE – NOTIFICATION OF ETHICS APPROVAL FROM ANOTHER ETHICS COMMITTEE

Project: Teaching Sustainability to Engineering Students in the Light of Threshold Concept Theory

Thank you for your correspondence notifying this office of your project's review and approval by a non-UWA Research Ethics Committee.

It is noted that you have ethics approval from University of Waikato Human Research Ethics Committee, approval number FEDU027/20.

The students and researchers identified as working on this project are:

Name	Institution Details	Role
Dr Sally Male	School of Engineering	Chief Investigator
Dr Wendy Fox-Turnbull	University of Waikato	Co-Investigator
Dr Jonathan Scott	University of Waikato	Co-Investigator

Student(s): Sina Enteshari

Although The University of Western Australia reserves the right to subject any research involving its staff and students to its own ethics review process, in this case, the UWA Human Ethics Office recognizes the existing approval of the non-UWA ethics committee. Any conditions for the recognition of the external HREC's existing approval are listed below:

Special Conditions

1. *Approving HREC to receive annual reports, amendments and notification of adverse events*
2. Subject to compliance with local UWA, State, Commonwealth and international health directives. Some of these directives may delay the work beyond the timeframe available to the research team, for example a student project. In such cases we recommend the research team (PhD student and supervisors) redesign their research to accommodate online fieldwork, and then re-submit for review.

You are reminded that the approving ethics committee remains the monitoring committee for this project. You must correspond with them for matters regarding amendments, adverse events, annual and final reporting.

If you have any queries, please contact the HEO at humanethics@uwa.edu.au.

Please ensure that you quote the file reference – RA/4/20/6216 – and the associated project title in all future correspondence.

Yours sincerely

Mark Davies
Manager, Human Ethics

FGD Sample Questions

Appendix A.1: Focus Group Discussion with Students

Please NOTE: These questions are for my use ONLY and to know what are the main topics that needs to be discusses! Thus, these questions are subjected to change according to the group and response.

Q.1. Discuss the definition of sustainability? (Depending on the discipline presents, looking for different definitions and good discussion around that)

-How does this apply to your discipline?

Q.2. Reflecting on your studies (in your field) so far,

- How do you find the Sustainable Engineering paper related to your studies?

Q.3. Which topics taught in Sustainable Engineering paper did you find most BENEFICIAL to you?

-Why do you see it in that way?

Q.4. Which topics/ideas taught in Sustainable Engineering paper did you find HARD to understand?

-Why so?

- What aspects need improvement? Why? How?

Q.5. Did you experience any 'light bulb' moment during the course?

Appendix A.2: Focus Group Discussion with Academicians

Please note: These questions are subject to change as per responses of the participants. Thus these are not final questions.

Q.1. Discuss the definition of sustainability and how hard was it to teach it to different disciplines? (Opening question to make Academics reflect on their experience and set the goal in place for the rest of the discussion)

Q.2. Do you think the students have a conceptual understanding of Sustainability?

Q.3. Which topics taught in Sustainable Engineering paper did you find most BENEFICIAL to students (list below)?

-Why do you see it in that way?

-Does this apply to all engineering discipline?

Q.4. Which topics taught in Sustainable Engineering paper did you find HARD to explain to students (list below)?

-Why so?

-Does this apply to all engineering discipline?

- What aspects need improvement? Why? How?

Student list for Q.3 and Q.4:

- Chemical and Biological
- Civil
- Electronics
- Environmental
- Materials and Processing
- Mechanical
- Software

Q.5. Did you experience any 'light bulb' moment during the course?

Interview Sample Questions

Perception:

1. What does the term "*sustainability*" mean to you?
2. In terms of software engineering, how would you define "*sustainability*"?
3. How and to what extent is "*sustainability*" ingrained in your discipline, in your opinion?
4. Could you tell me about student's perception of "*sustainability*"?

Course on sustainability

5. What do you think a "*sustainability*" course for software engineers should cover?
6. What are your thoughts on teaching pure environmental studies to software engineers?
7. What are your thoughts on teaching life cycle analysis to software engineers?
8. What will the LCA be good for in your field?
9. What kinds of projects do you think you'll see for LCA that a software engineer could work on?
10. How would you improve the way "*sustainability*" is being taught to software engineers? Would this require a significant shift?

"Software Engineering Methodology" module

11. What component of the "Software Engineering Methodology" module do you think makes students believe it is a better fit for them in terms of "*sustainability*"?
12. When teaching the "Software Engineering Methodology" module, what concept(s) have you found to be conceptually difficult for students to grasp?
13. What do you believe should be changed in the current paper to better serve the needs of software engineers who want to learn about sustainability?

Questionnaire Sample



Sustainable Engineering_ENGEV342-19A (HAM)

Thank you for agreeing to participate in Sustainable Engineering 2019 questionnaire. This questionnaire is focused on students' knowledge of sustainability in engineering as well as how they value it. Although the questionnaire is voluntary, your participation is greatly appreciated and essential to the future of engineering education at the University of Waikato. This questionnaire is part of a more extensive report, which will identify threshold concepts of sustainability in engineering. Through your responses, I will gain a better understanding of what areas students are interested in as well as where the University needs to improve to provide a better understanding for all engineering discipline towards sustainability.

Your responses will be **anonymous**. The survey should take around **10 minutes**. There are no foreseeable risks associated with this project. However, if you feel uncomfortable answering any questions, you can withdraw from the questionnaire at any point.

Section 1 (General Questions):

Q.1. What is your subject area?

- Chemical and Biological
- Civil
- Electronics
- Environmental
- Materials and Processing
- Mechanical
- Software
- Others:

Q.2. Select the project (assignment) you were involved in:

- Subdivision of Peacockes Rd
- Upgrade of the Hamilton Wastewater Treatment Plant
- Ruakura Landport
- Waikato Expressway
- Huntly Power Station Upgrade
- Electric vehicles in Australia and New Zealand
- Hydrogen cars for Hamilton
- Pumped storage for large scale electricity storage
- Batteries for domestic, industrial and large scale storage
- Robotics in Agriculture and Forestry Industries
- Taupo geothermal
- Cybersecurity
- Power outages and solar flares
- Parker solar probe
- 2003 Eastern seaboard power outage
- 2011 Tōhoku earthquake and tsunami
- Mars Curiosity rover
- Densification of Hamilton vs urban spread
- Establishing a cycle/scooter network in Hamilton



Q.3. Did your project help in any way in your understanding of sustainability in engineering?

- Yes
- No

Explain why/why not?

Section 2 (Discipline Focus Questions):

Answer these questions according to your study discipline (field of study).

Q.4. How important is sustainability practice in your field of study?

- Extremely important
- Moderately important
- Not at all important
- Very important
- Slightly important

Q.5. Does your field of study have the influence to help make any difference on **ENVIRONMENTAL** issues like waste, resource consumption, and water use?

- Definitely yes
- Might or might not
- Definitely not
- Probably yes
- Probably not

Q.6. Does your field of study have the influence to help make any difference on **SOCIAL** issues like safety and security, education, and health and wellness?

- Definitely yes
- Might or might not
- Definitely not
- Probably yes
- Probably not

Q.7. Does your field of study have the influence to help make any difference on **ECONOMIC** issues like unemployment, inflation, and local business/local economy?

- Definitely yes
- Might or might not
- Definitely not
- Probably yes
- Probably not

Q.8. How confident are you that you have mastered sustainability in engineering that is relevant to your field of study?

- Extremely confident
- Somewhat confident
- Not at all confident
- Very confident
- Not so confident



Q.9. The Triple bottom line approaches sustainability by considering?

- People, the economy, and liveability
- The economy, the planet, and equity
- Social, Economics, and Environmental
- Equity, viabilities, and liveability
- All of the above

Q.10. Can you name all ISO 14000 standards family?

- Yes
- Maybe
- No

Q.11. Is Environmental management related to your study field?

- Definitely yes
- Probably yes
- Might or might not
- Probably not
- Definitely not

Q.12. How difficult (troublesome) was it to learn about.....?

	Extremely easy	Somewhat easy	Slightly easy	Neither easy nor hard	Slightly difficult	Moderately difficult	Extremely difficult
Risk analysis							
Functional block diagram							
Fault tree							
Resilience							
Resilience curve							
Environmental impact assessment							
Resource management act							
Life cycle assessment							
Environmental law and regulation							
Carbon account							



Q.13. What are the critical ideas/concepts in Sustainable engineering in your discipline?

Section 3 (Personal Preference Questions):

Answer these questions according to your personal preference.

Q.14. How important is sustainability practice to you (personal preference)?

- | | |
|---|---|
| <input type="checkbox"/> Extremely important | <input type="checkbox"/> Very important |
| <input type="checkbox"/> Moderately important | <input type="checkbox"/> Slightly important |
| <input type="checkbox"/> Not at all important | |

Q.15. How confident are you that you have mastered sustainability in engineering?

- | | |
|---|---|
| <input type="checkbox"/> Extremely confident | <input type="checkbox"/> Very confident |
| <input type="checkbox"/> Somewhat confident | <input type="checkbox"/> Not so confident |
| <input type="checkbox"/> Not at all confident | |

Q.16. Please indicate whether you:

	Yes	Partially	No
Are interested in sustainability?			
Are sure of what sustainable development means?			
Feel comfortable using sustainable development in your field of study.			

Q.17. Have your world view towards our action and decision as an engineer has changed ever since introduced to the sustainability concepts?

- Yes
- Maybe
- No



Q.18. Do you think you have a personal responsibility to help make any difference on **ENVIRONMENTAL** issues like waste, resource consumption, and water use?

- | | |
|---|---------------------------------------|
| <input type="checkbox"/> Definitely yes | <input type="checkbox"/> Probably yes |
| <input type="checkbox"/> Might or might not | <input type="checkbox"/> Probably not |
| <input type="checkbox"/> Definitely not | |

Q.19. Do you think you have a personal responsibility to help make any difference on **SOCIAL** issues like safety and security, education, and health and wellness??

- | | |
|---|---------------------------------------|
| <input type="checkbox"/> Definitely yes | <input type="checkbox"/> Probably yes |
| <input type="checkbox"/> Might or might not | <input type="checkbox"/> Probably not |
| <input type="checkbox"/> Definitely not | |

Q.20. Do you think you have a personal responsibility to help make any difference on **ECONOMIC** issues like unemployment, inflation, and local business/local economy?

- | | |
|---|---------------------------------------|
| <input type="checkbox"/> Definitely yes | <input type="checkbox"/> Probably yes |
| <input type="checkbox"/> Might or might not | <input type="checkbox"/> Probably not |
| <input type="checkbox"/> Definitely not | |

If you'd like to add any comments, concerns, or ideas about sustainable Engineering questionnaire, please do so here.

If you'd like to add any comments, concerns, or ideas about sustainable Engineering paper, please do so here.

Thank you for your time. We hope this study could benefit us all and help to make sustainability more related to your disciplines.

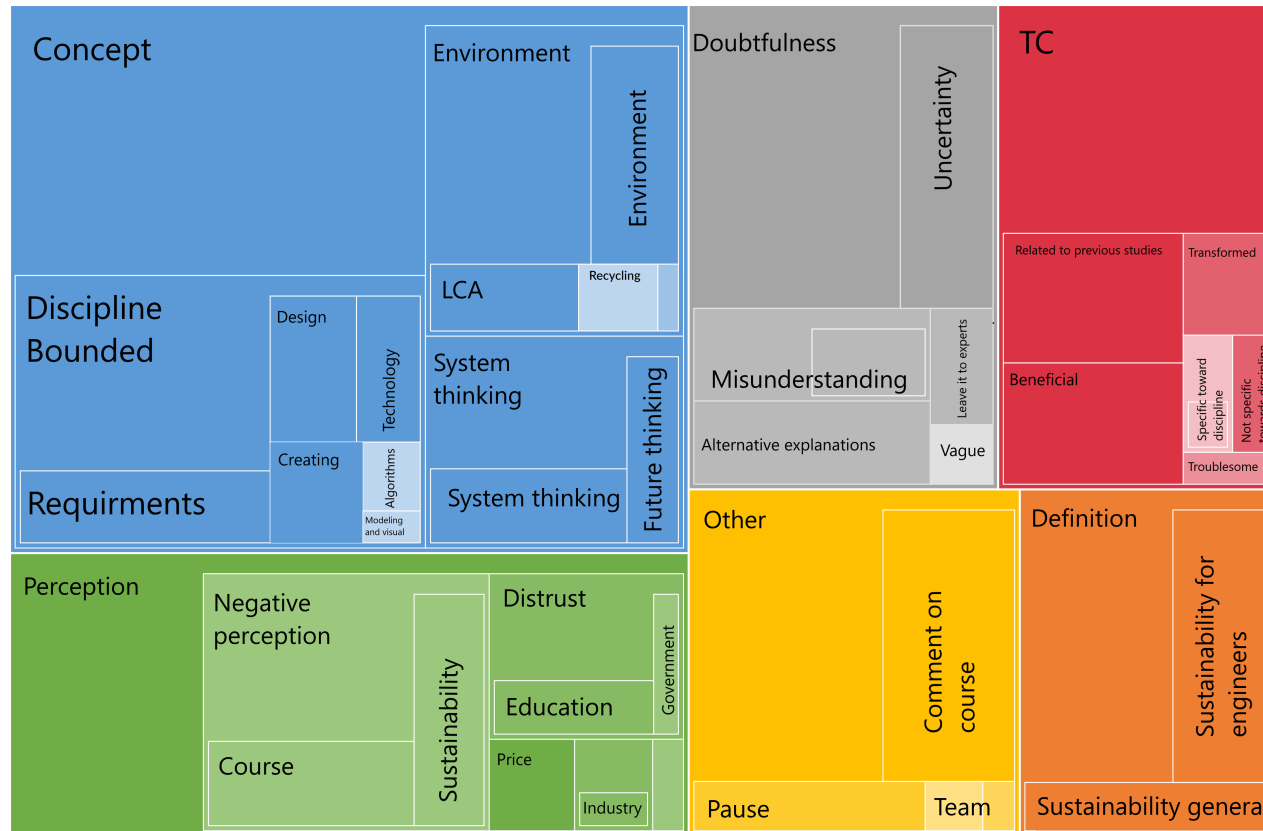
Data analysis

A simple description of all Phases' themes and codes. The meaning and purpose behind a few of the themes and codes that were used in this study to analyse the data is provided here. The themes are not directly related to each other.

Name	Description
Concept	A theme that is used to incorporate ideas of what something is or how it works in regards to participants' discipline and perceptions.
Discipline Bounded	Specific to a particular discipline
Algorithms	An algorithm is a sequence of steps executed by a computer that takes an input and transforms it into a target output.
Creating Design	To make or produce (something): to cause (something new) to exist. To devise for a specific function or end.
Modelling and visual	To produce a representation or simulation; the act or process of interpreting in visual terms or of putting into visible form.
Requirements	Requirements engineering is the process of defining, documenting, and maintaining requirements in the engineering design process.
Technology	Advancement made by engineers.
Environment	Elements that cover all the Concepts relating to environmental studies.
LCA	Life Cycle Assessment.
Pollution	Concept of pollution.
Recycling	Concept of Recycling.
System thinking	Systems thinking is a holistic approach to analysis that focuses on the way that a system's constituent parts interrelate and how systems work overtime and within the context of larger systems.
Future thinking	A holistic approach in which future generation is considering in planning.
Definition	An explanation of the meaning of a word, phrase.
Sustainability definition	Sustainability definition in general.
Sustainability for engineers	Sustainability definition specific to disciplines.
Doubtfulness	Lacking a definite opinion, conviction, or determination.
Alternative explanations	To tell, show, or be the reason for or cause of something.
Leave it to the experts	Lack of care towards certain aspects.
Misunderstanding	Different explanation.
Uncertainty	Lacking a definite opinion, conviction, or determination.
Vagueness	Not clear in meaning: stated in a way that is general and not specific.
Other	Elements not discovered that are not within the study boundary but useful to explain the perception and behaviour of participants.
Comment on the course	Comment on the course in general.
Pause	Pause to think or pauses that show uncertainty.
Team	Team work comments.
Perception	The way you think about or understand someone or something.
Distrust	To have no trust or confidence in.
Distrust of education	To have no trust or confidence in education and university.
Government control	To have no trust or confidence in government; political statement.
Industry	Experience in industry or comment relating to industry.
Negative Perception	Negative perception of participants on the course.
Negative perception of course	Negative perception of participants in the course.
Negative perception of SUS	Negative perception of participants in sustainability.
Nuisance	Annoying and tedious.
Price	Heavy focus on money and the way it influences sustainability in participants' perception.
TC	Threshold Concept.
Beneficial	Useful aspects or concepts from participants' point of view.
Not troublesome	Not conceptually complex or challenging.
Related to previous studies	Very similar to disciplines' previous learning.
Specific toward disciplines	Directly related to disciplines' previous learning.
Transformed	Sign of transformed behaviour or way of thinking.
Troublesome	Challenging in a conceptual way or hard to do from participants' point of view.

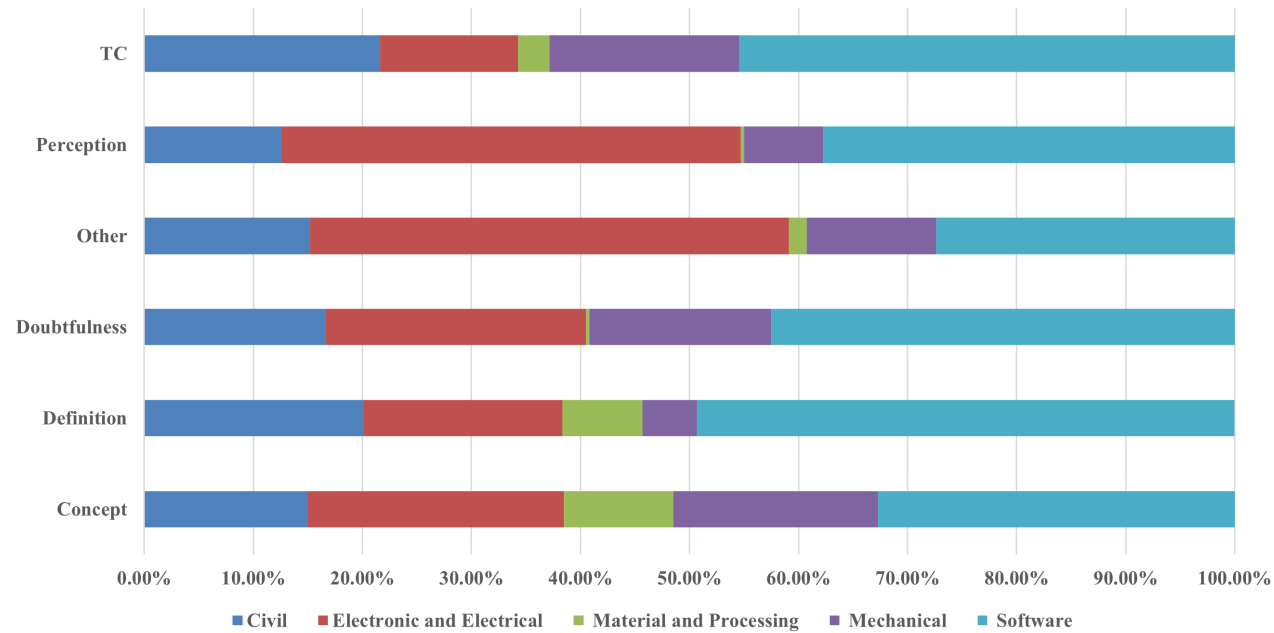
Phase One Data analysis

Themes and sub-themes in Phase One



Using NVivo to analyse the data allowed us a more holistic understanding of the underlying themes and codes. If there is a larger box next to a category, then a larger percentage of the transcriptions fall into that category. For instance, most transcriptions were given to the concept category, since that's where the greatest space is in the graph. The "discipline-bounded" sub-theme of the "concept" theme also occupies a comparatively larger space.

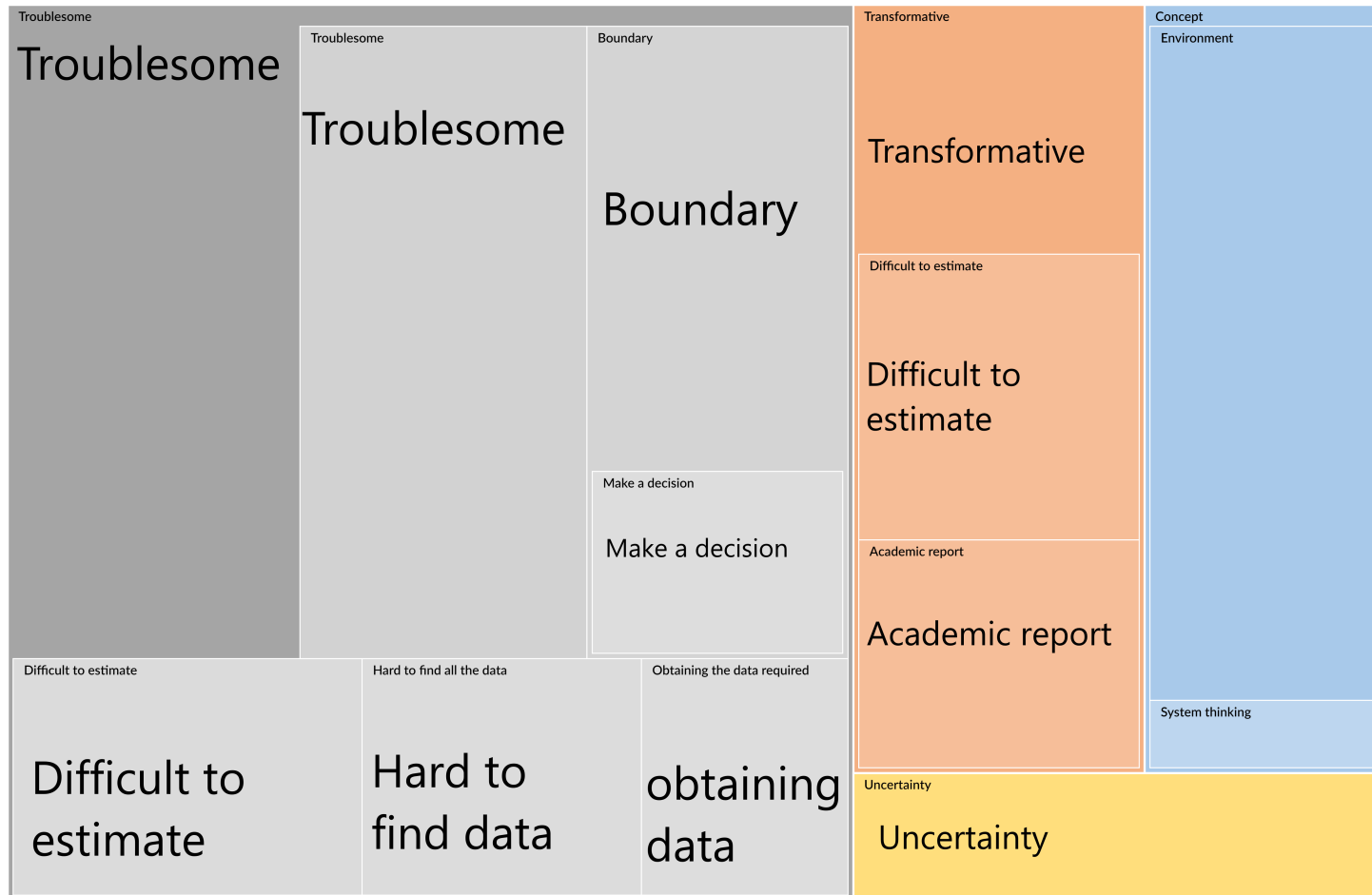
Distribution of disciplines' contributions in Phase One - Focus group and interview themes ranked based on participants' contributions



NVivo was used to help flesh out the details of each discipline's contribution. The graph can aid in the analysis of various disciplines and classifications for various themes. For example, when it comes to the TC theme, material and processing has contributed the least, while software has contributed the most.

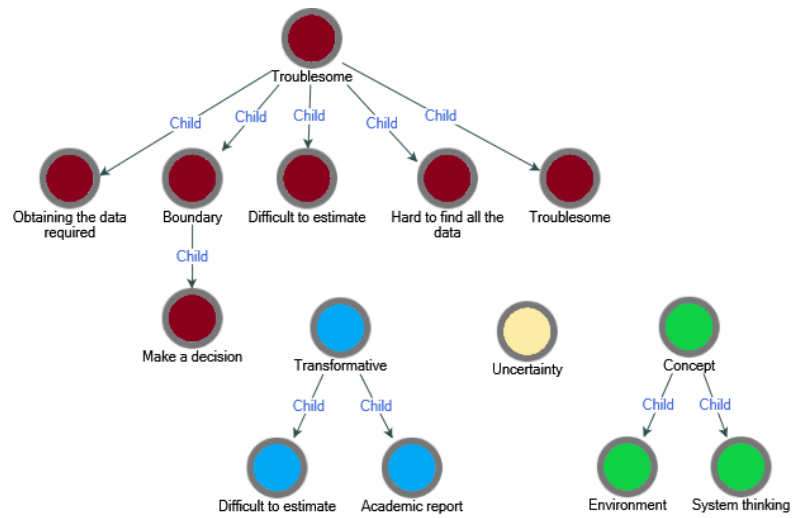
Phase Two Data Analysis

Themes and sub-themes in Phase Two



Box sizes refer to the amount of each theme's/element's coding intensity - in other words, the percentage of words assigned to certain themes.

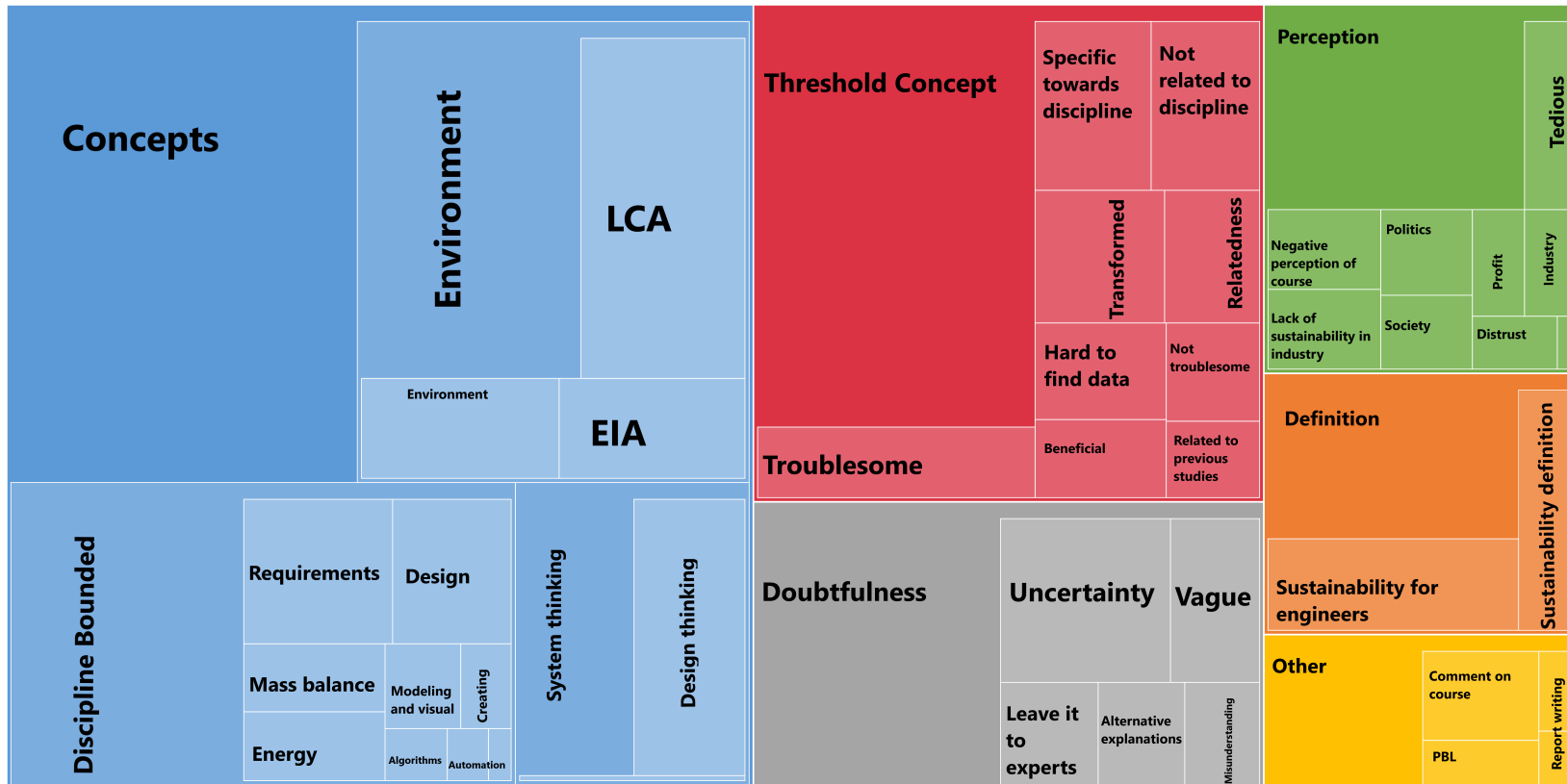
Themes and sub-themes relationship in Phase Two



A simple child and parent relation based on the themes and sub-themes found in Phase Two.

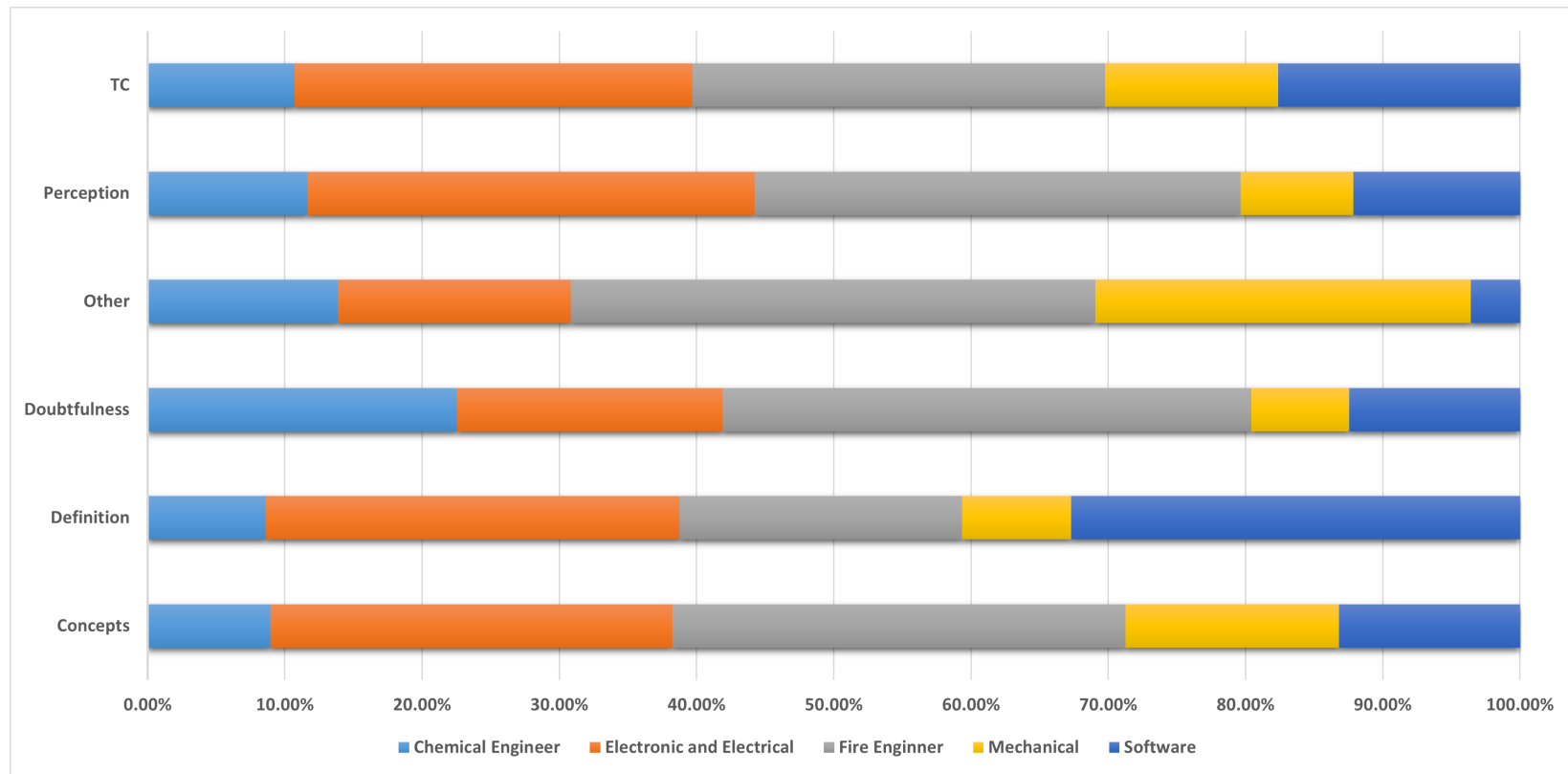
Phase Three Data Analysis

Themes and sub-themes in Phase Three



Box sizes refer to the amount of each theme's/elements' coding intensity - in other words, the percentage of words assigned to certain themes.

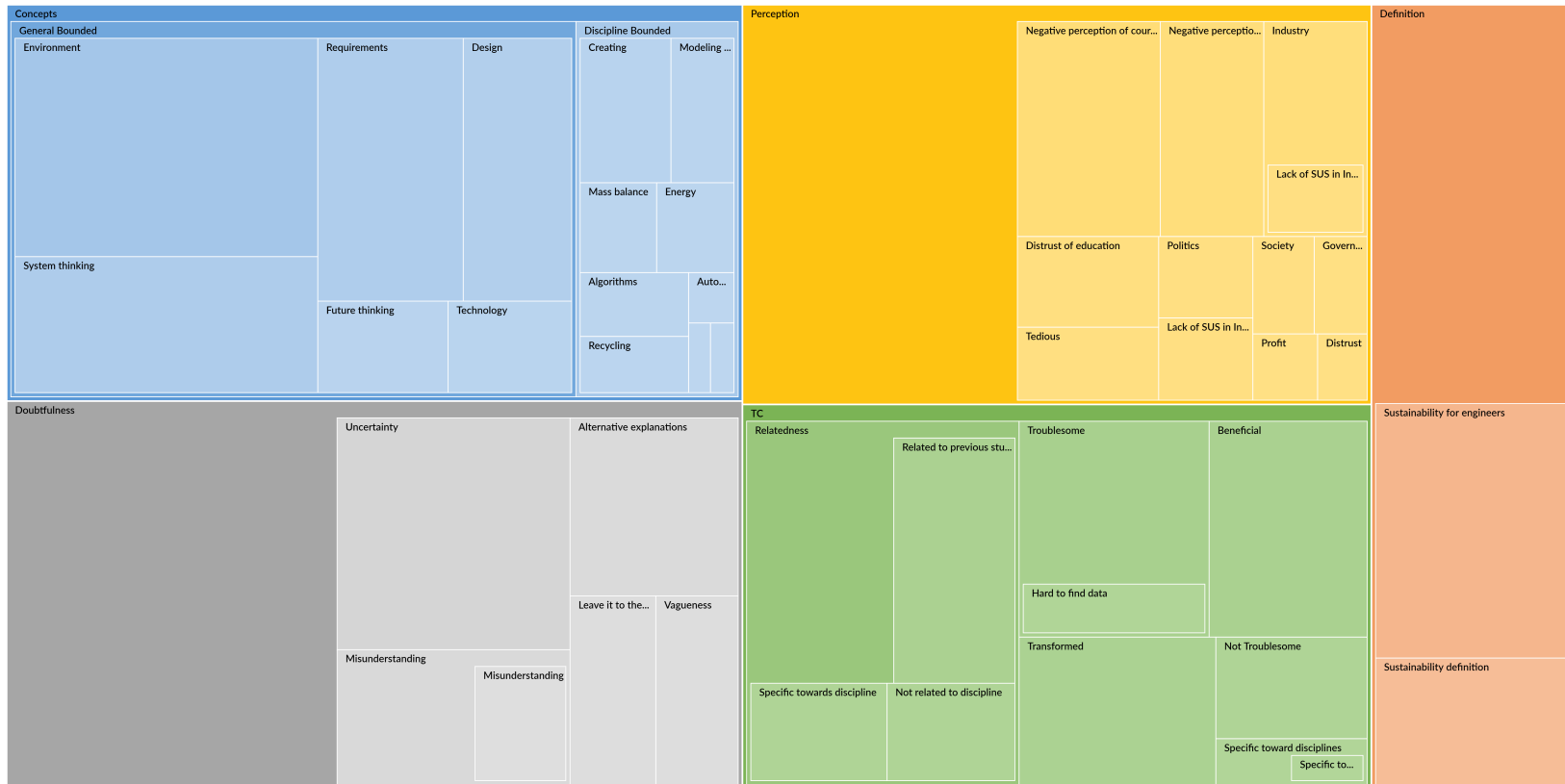
Distribution of disciplines' contribution in Phase Three - Focus group and interview themes ranked based on participants' contribution.



NVivo was used to help flesh out the details of each discipline's contribution. The graph can aid in the analysis of various disciplines and classifications for various themes. Some disciplines had more input than others in certain themes. For example, SE and EEE contributed more in defining sustainability.

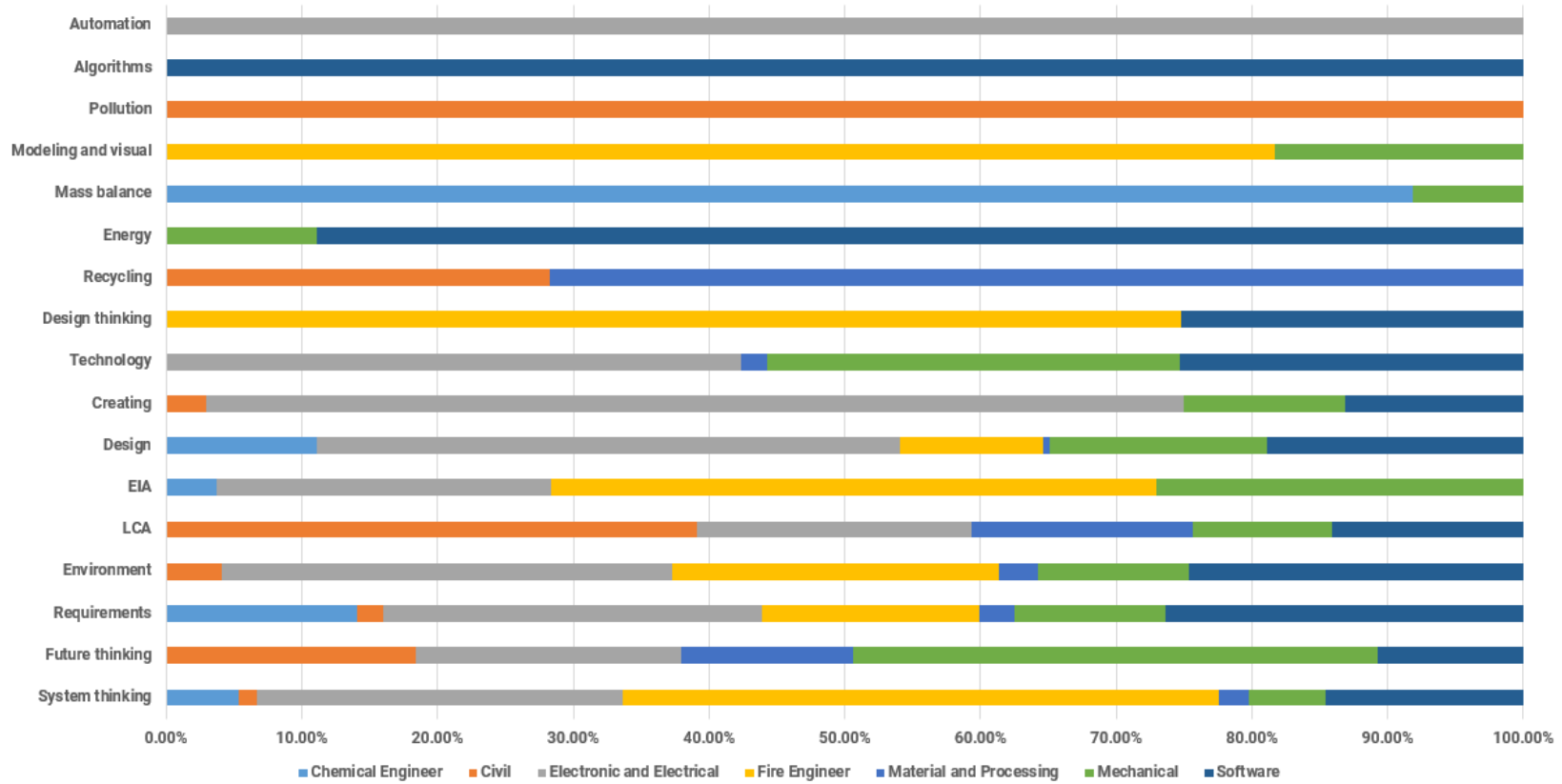
Phase One and Three Data Analysis Combined

Distribution of major themes and sub-themes for Phases One and Three



Box sizes refer to the amount of each theme's/element's coding intensity - for example, Concept has a larger box, indicating that it has a higher coding intensity as compared to Definition. Furthermore, inside the Discipline bounded box, Creating has a greater coding intensity, represented by the larger box.

Theme of Concept codes found in Phase One and Phase Three data



Theme of Perception codes found in Phase One and Phase Three Data

