Contextual Comparing and Constraining

A Grounded Theory Study of Undergraduate Engineering Group Design Projects

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Abstract

Engineering design projects are significant components of engineering undergraduate students' programmes and can be transformative in developing important professional competencies such as communication and teamwork skills.

This study contributes to the limited knowledge in qualitative research into undergraduate engineering design projects by exploring the questions: *what are the prominent concerns of engineering students undertaking such design projects* and *how do they manage these*? The study involved an exploration of undergraduate Chemical Engineering students undertaking a substantial design project at the University of Strathclyde.

Student groups were observed in supervisory meetings to sensitise the researcher and accompany the primary data collection method of intensive interviews. Informing the approach to the study was Grounded Theory (GT) methods for analysis, these involved techniques such as initial (line-by-line) coding; memo-writing; focused coding and theoretical sampling. Following extensive coding and categorisation of concepts, data from other studies in engineering design projects conducted by Goncher (2012) and Morgan (2017) were introduced and integrated into the emerging understanding.

This research demonstrated that students' beliefs around the significance of the design projects; their socialisation with others and their expectations of the educational setting impacted their approach to design significantly. Students engaged in social processes related to *comparing* and *constraining* to manage a range of contextual factors. *Comparing* involved evaluating various design ideas and solutions to make sense of open-ended problems; while *constraining* refers to the methods used to limit the design space and context to reduce ambiguity. These processes also relate to both social dynamics (such as collaborative efforts and information sharing) and technical factors (like minimising risks and relying on models). Students use such strategies to refine their designs iteratively and align with project requirements to constrain their emergent designs. Supervisory feedback also plays a crucial role in guiding these processes, with effective feedback helping to constrain creative exploration within feasible boundaries.

بسم الله الرحمن الرحيم

“Peace on you for the patience you observed.
So, how excellent is the ultimate abode.”
(Al-Quran, The Thunder, verse 24)

In memory of Taya Umar, who is awake while we sleep.

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Chapter 1. Introduction to the Thesis

This chapter provides an overview of the presented thesis. The chapter begins with the wider motivations and context which informed the conception of the research endeavour presented in this thesis. The aims of the research and how the research approach was developed are then described. Thereafter the relevance of the study, key contributions and associated limitations are outlined. The chapter closes with a summary of the structure of the remaining chapters.

1.1 Motivations

The Engineering Council (2014) define “design” as:

> … the creation and development of an economically viable product, process or system to meet a defined need. It involves significant technical and intellectual challenges and can be used to integrate all engineering understanding, knowledge and skills to the solution of real and complex problems. (p.19)

It is unsurprising then, that Dym et. al’s (2005) influential works on *Design Thinking* emphasises that design projects have become a fundamental component of engineering curricula. These serve as both formative and culminating academic experiences that involve the integration and application of knowledge and skills acquired and developed throughout a student’s education. Historically, the inclusion of projects in engineering education reflects a pedagogical shift towards experiential learning, emphasising the need for practical, hands-on experiences that simulate professional engineering practice (Dutson et al., 1997). These projects are designed to provide engineering students with an opportunity to tackle complex and open-ended problems.

In previous work conducted within the Chemical & Process Engineering department at the University of Strathclyde, Fletcher et al. (2017) surveyed chemical engineering students and alumni on various aspects relating to the transition to the workplace. Their findings, consistent with the literature around professional engineering competencies (Male et al., 2011a; Passow, 2012; Passow & Passow, 2017), suggested that among the most important skills for surveyed chemical engineering students and alumni, were those relating to transversal skills, namely communication, teamwork, data analysis and problem-solving skills. However these skills prove to be complex and multi-faceted, as evidenced by the work of Male et al. (2011b) who found that these generic skills are made up of components with varying degrees of importance and that there is no consensus on how these skills are understood by practicing professional (Darling & Dannels, 2003). Furthermore, Lutz and Paretti (2021) note that beginning as far back as "1918, reports have emerged periodically highlighting the underpreparedness of engineering graduates for work" (p. 132), and studies continue to reveal that these skills, in various engineering education contexts, are lacking in graduates as they enter the workplace (Fletcher et al., 2017; Male et al., 2010; Ramadi et al., 2016).

It has been proposed that group-based design projects offer opportunities to develop these professional skills such as teamwork, project management, and communication as well as, design thinking which inherently involves problem-solving and data analysis (Dym et al., 2005; Razzouk & Shute, 2012). Some institutions have gone as far as adopting project-based learning as the modus operandi for entire engineering programmes with design projects a recurring feature (Kolmos et al., 2006). The positive effects of such design projects have been evidenced through self-evaluative, pre- and post-survey research in various contexts (Fletcher & Harrington, 2018; Gavin, 2011; Picard et al., 2022). Design projects are therefore useful sites for deeper exploration, especially given this association with professional competency and identity formation (Lowe et al., 2022).

Although design projects have been widely recognised as essential educational experiences for developing students' professional competencies (Hadim & Esche, 2002; Helle et al., 2006; Lowe et al., 2022; Lutz & Paretti, 2017; Mills & Treagust, 2003), they remain inevitably embedded within the academic context. The Institution of Chemical Engineering (IChemE), the global accreditor for chemical engineering degrees, anticipate that design projects should "simulate so far as is reasonably possible the real world whilst acknowledging the constraints of the educational setting, course aims and students stage of development" (IChemE, 2017, p. 3).

This tension presents a unique challenge for educators, who must navigate between providing an authentic design experience whilst adhering to the structured requirements of the academic curriculum. Constraints such as limited time, resources, and the need to meet, and assess, specific learning outcomes can restrict the developmental scope of such projects, potentially diminishing their ability to fully "simulate" professional design work (Goncher & Johri, 2015). Dannels (2003) and Paretti (2008), in their qualitative studies of capstone design projects and students' social practices therein, demonstrated how the academic context and constraints of design impacted students attitudes and practices to design. In both studies, many students approached design with an academic orientation, despite efforts from educators to mirror professional design features. It is clear that there is a critical need for design projects to be explored further to investigate the associated educational impact within these constraints and determine which features contribute to these valuable learning experiences for students.

This wider aim means that there is a need, first, for a better understanding of academic design projects and students' practices in relation to these before it is possible to understand how such transversal competencies may embed within design. In addition, some have argued that the consistent findings around graduate skills deficiencies has demonstrated that the outcomes-based approach has fallen short in capturing the breadth of learning from a holistic perspective (Walther & Radcliffe, 2007). Others have added that engineering education research should utilise more elaborate methods for approaching studies to explore learning activities (Johri et al., 2014) like those employed in the studies of Dannels (2003) and Paretti (2008) cited above.

For example, the group-based, interactional nature of many design projects introduces complexities related to group dynamics and project management. Group work can be a dialectical phenomenon; while it provides valuable opportunities for collaboration and learning, it can also lead to challenges such as unequal participation, conflicts and coordination difficulties (Mercier et al., 2023). These issues can detract from the overall learning experience and may require intervention from instructors to ensure that all students are able to contribute meaningfully to, and benefit from, the project. Yet, from a competency perspective, this nuanced understanding may simply be categorised under a broad umbrella term of “teamwork skills”.

Factors such as the level of complexity, the degree of student autonomy (Pisani & Haw, 2023), and the nature of academic support (Paretti, 2008) can all influence student development through design experiences. It has been proposed by Starkey et al. (2016) that design requirements that offer a high degree of student autonomy and encourage exploration and experimentation are more likely to foster creativity and innovation, whereas highly structured projects may limit opportunities for independent problem-solving.

With respect to design as an area of investigation in and of itself, there is a significant body of literature which explores the design practices of engineering students and professionals in various contexts and design tasks (Atman et al., 1999, 2007; Atman & Turns, 2001; Dorst & Cross, 2001; Lemons et al., 2010). Such studies have largely relied on protocol analyses for tasks that are usually observed in the timeframe of hours at most and usually take place in laboratory settings.

Despite the breadth of complexity around design and associated practices, qualitative, naturalistic inquiry into engineering projects in educational settings remains limited. There is a need for further work in this area, that sits in between the decontextualised, competency-mapping macro-scale understanding and the short-duration, highly controlled, micro-scale analyses of design practice. There is a need for exploration between the two, through investigations of sustained design activity at the meso-scale, in the specific and rich contexts where these valuable competencies may be deployed and developed whilst accounting for beliefs and formative experiences of participants (Tessmer & Richey, 1997). There is a recognition of this in the broader design literature, and there have been a growing interest in qualitative studies of “design in the wild”. (Adams et al., 2018; Shroyer et al., 2018)

Morgan (2017) and Goncher (2012) have contributed substantially to a more holistic qualitative understanding of engineering design projects area in their respective contexts. These works have demonstrated how more in-depth and prolonged studies of students' practice over entire design projects can offer meaningful insights for engineering design education. Morgan offered a unique approach of utilising *Case Study Research* and *Constructivist Inquiry* in general can act as a paradigm through which design can be understood by students and educators to shape their practices (Morgan & McMahon, 2015, 2017). Goncher, on the other hand, focussed on the roles of institutional and organisational constraints in shaping students design practices, as part of an analysis informed by nested structuration theory. These studies demonstrate the role that explorative, qualitative studies in this field have in fostering more nuanced understandings of context in relation to engineering design projects (Goncher, 2012; Goncher & Johri, 2015).

1.2 Research Aims

Given the complexities and variability of engineering design project experiences, there is a clear need for research that goes beyond outcome- and competency-based evaluations to explore the underlying conditions, processes and practices that contribute to students' development. There remains a significant gap in understanding of how students engage with these group projects as lived experiences, particularly with respect to the complexities and variabilities introduced by the social context.

Following from the earlier outlined motivations, there needs to be more detailed and qualitative research endeavours to add to the limited field, and integration of such studies to account for variability of design contexts and settings.

This research then aims to answer two main research questions:

> **RQ1:** What are undergraduate students' salient concerns related to engineering design projects?

> **RQ2**: How do undergraduate students manage their concerns related to engineering design projects?

Here, "concerns" are understood be those considerations during design which draws significant focus and attention from students. Ultimately, these are aspects which were deemed important to the students under investigation. Such questions are framed in this manner so as to not presume students' motivations and practices; while the literature and theoretical frameworks related to competency development or design may have been useful lenses, these may not necessarily be what informs students in practice. Indeed, the literature in relation to these areas were only thoroughly investigated after the completion of the study itself, as per the research approach taken (see section 1.3 and Chapter 3). Instead, the phrasing is presented as such to highlight the centrality of students' perspectives on the lived phenomenon of engineering design projects. To answer questions, the research approach must be well-suited for exploration of complex, uncontrolled, context-dependent phenomena such as the student experience in design projects, as indeed it is found in practice, as this allows for the generation of insights that are directly informed by the perspectives of those involved. As Minneman (1991) suggests, "designing should be studied in situ, asking "what is going on here?" (p.66).

1.3 Research Approach & Limitations

A grounded theory approach offers a promising avenue for addressing this gap in the wider literature. Grounded theory is a qualitative research methodology that involves the systematic collection and analysis of data to develop a socio-psychological theory that is grounded in the experiences of the participants.

Grounded Theory (GT) is a qualitative research methodology first developed by sociologists Barney Glaser and Anselm Strauss in the 1960s. Originating from their collaboration on studying the social processes surrounding death and dying in hospitals, their seminal work, *The Discovery of Grounded Theory* (1967), laid the foundation for this approach. Grounded Theory emerged as a critique of the dominant positivist methods in sociology, which emphasized hypothesis testing and quantification, and the proliferation of generalised, grand theories. Glaser and Strauss instead advocated for the generation of theory directly from empirical data. Grounded Theory promotes an inductive process where data collection and analysis occur simultaneously, allowing theoretical concepts to emerge organically from the data rather than being constrained by preconceived theories (Glaser & Strauss, 1967). Minneman's (1991, p. 66) earlier quote about how design should be studied could be considered an echo of Glaser and Strauss (1967) when they stated that the purpose of developing theoretical concepts is to understand "what is going on in the area studied" (p. 23).

The key methods and techniques of GT include data coding, constant comparative analysis, memo-writing, and theoretical sampling. Data coding involves breaking data into smaller parts and systematically comparing them to identify patterns and themes. The constant comparative method requires researchers to continuously compare new data with existing and tentative codes and categories, iteratively refining these as new data is analysed.

All qualitative research has significant limitations in relation to inherent researcher bias and so an emphasis has been placed on addressing issues around these limitations by adopting Walther et al.'s (2013, 2017) model around validation criteria for qualitative research. This suggests how GT can be an effective approach to address these concerns around quality. In this work, there is a strong emphasis on the presentation of contextual data alongside analysis. Nevertheless, the research remains an interpretation of the data and so cannot be treated as universally applicable where authoritative generalisable claims are made. The research offers possible explanations and hypotheses with evidence – it is left to the reader to decide if they find the interpretation sound.

By employing a GT approach, this thesis aims to investigate the practices of engineering students in group design projects, with a focus on understanding the processes through which students navigate their self-identified challenges associated with design. The importance students' attach to such challenges helps position the social phenomenon of design first and foremost interpretively from the perspectives of participants. This self-identification allows for access into the informed perspectives of students' which may be unreachable for researchers or educators, owing to their own perspectives. For example, design, could be viewed as *troublesome knowledge*, and aspects relating to possibilities for multiple-solutions may be conceived as a *threshold concept* related to design, which are fundamentally transformative, irreversible and integrative concepts (Meyer & Land, 2003). Hence, students' perspectives are likely to yield more relevant insights about the design experience as it is understood from their position – which is critical for educators to understand if they are to effectively promote student development and learning.

1.4 Relevance of the Thesis

The findings of this work are expected to provide a nuanced understanding of the student experience in design projects. Despite these being positively association with professional competency development, there is a need to first understand the practices of students and the features of design that they hold important. This deeper understanding of design can inform educators' development of design project to align these better with the wider educational aims in situated contexts.

In addition, the research, in line with the principles of Grounded Theory, will offer a theoretical model to assist students as they develop professional competencies by demonstrating practices and factors that may inhibit or enable professional skills development through design. With this model, it is hoped that students can benefit most from these critical educational experiences. This research also aims to inform educators about best practice for fostering graduate competencies by outlining critical features of curriculum development in design that should be carefully considered. Seemingly minute factors may have significant impact on the benefit student are able to draw from engineering design project experiences.

Finally, the research demonstrates the value of the GT method to explore rich contextual settings such as engineering design projects. Reflexively, in terms of my own development, I hope to carry on developing the Grounded Theory presented in this research to expand its scope beyond the engineering field and English-speaking world; exploring domain- and cultural-specific aspects that may further refine the theory. In addition, the approach will be used to explore further research in non-group settings to develop a deeper understanding.

1.5 Contributions to Knowledge

The thesis presented, provides offers three specific contributions to the body of knowledge in the area of engineering design projects.

First, the thesis presents original, rich and detailed descriptions of social interactions that took place in the context of an undergraduate engineering design project, specifically in the field of chemical engineering.

Second, the use of the Grounded Theory method in the context of undergraduate chemical engineering design projects, has developed insights into how students navigate the inherent open-endedness of such projects through the concept of *comparing* and *constraining* with respect to various aspects.

Finally, the comparative analysis of secondary data across three different settings has pushed the original context-specific theoretical interpretations to a more abstracted grounded theory, drawing out commonalities across these various contexts. Furthermore, the use of data across different conditions and instances of undergraduate engineering design projects to inform analytical, qualitative inquiry is itself a valuable contribution given the little established work t is in this area.

1.6 Structure of Remaining Chapters

Chapter 2 introduces the journey of this thesis's inception by discussing the backdrop of graduate competencies and how project-based learning offers significant opportunities for competency development. In an engineering context, project-based learning is often coupled with design and both are discussed together, along with their relevance to competency development. Thereafter, an argument is made for moving away from competency mapping to more holistic understanding of students' development, to yield more meaningful insights. Qualitative studies around engineering design projects are then presented, demonstrating the value of such research.

Chapter 3, in the interest of research rigour, outlines the framework which informed the methodology along with a detailed discussion around the methodological considerations around Grounded Theory, the methodology that informs the research, with attention of my own reflexive journey in this new field of study.

Chapter 4 begins with a description of the research setting, with an emphasis of providing detailed description of the context and communicating openly the emergent approach to the methods adopted. Data collection strategies. Thereafter the chapter outlines the participants involved in the study and the approach to data collection along with developments that occurred through the research. The chapter then demonstrates, with examples, how the data was analysed using techniques from Grounded Theory.

Chapter 5 presents the results from data collection in tandem with analyses obtained from the coding process. It presents the main aspects related to students' design practices, competencies and contextual constraints; with patterns and findings supported with rich excerpts from interview data.

Chapter 6 presents an analysis and integration of the findings from this study to the works of Morgan (2017) and Goncher (2012). These also included rich narrative accounts and demonstrates the applicability of various prominent codes to context other than the setting from which these were developed.

Chapter 7 synthesises the findings into a unified Grounded Theory, the applicability of which is demonstrated through descriptions of how it applies to the various settings of design considered in Chapter 5 and Chapter 6. The theory demonstrates how the social context and constraints can impact students' behaviours and how they attempt to resolve their significant concerns. The chapter also touches the relevance the theory has to other literature to evidence its applicability in contexts other than those used to generate it.

Chapter 8 concludes the main text of the thesis and begins with a discussion of the contributions this theory makes to the wider field educational engineering design projects curricula, and recommendations that can be made to both educators and students to promote effective design project experiences. The chapter closes with a description of the limitations and possible areas of future work.

Chapter 2. Literature Review

2.1 Introduction

This chapter discusses the connections that the presented thesis has with the wider literature. In line with the Grounded Theory (GT) approach undertaken and agnostic perspective on the literature (discussed in greater detail in Chapter 3 and Chapter 4), this review did not inform the data collection or analysis itself. Rather, much of this chapter was undertaken after the completion of the analysis of primary data. This chapter opens with a review of literature relating to important engineering graduate competencies and associated competency gaps as previous work had been conducted and researched by the author of this work (Fletcher et al., 2017) and it was this preliminary research that directed the general area of study in engineering design projects. Thereafter, the argument is put forward that project-based learning and engineering design are an approach and area respectively which overlap often and are promising learning activities to develop those identified important competencies. Subsequently, it is demonstrated that research must move beyond mere competency mapping to understand better the complex notion of engineering identity formation. Finally, the chapter concludes with a discussion on situative perspectives of engineering education research and demonstrates the utility of exploring engineering design by reviewing some examples of qualitative, context-driven inquiry into aspects of engineering design projects.

2.2 Important (and Deficient) Competencies for Engineers

Implicit in engineering education, perhaps owing to the vocational nature of engineering itself, is the development of skills that will be particularly relevant to professional practice.

Walther et al. (2011) recognise that engineers are required to address major societal and global challenges and this was the main drive from content-based to outcomes-based engineering education, similar to Gutiérrez Ortiz et al. (2021) who view sustainable development as one such challenge. The goal of engineering education has shifted to develop professional competence, which is unsurprising given the vocational nature of the engineering profession. Therefore, it is unsurprising that the literature is saturated in relation to quantitative exploration of the importance of skills relevant to practice for professionals.

Passow (Passow, 2012; Passow & Passow, 2017) has investigated various engineering competencies as outlined by the accrediting body for US engineering faculties, the American Board of Engineering and Technology (ABET). Passow (2012) found that from their respondents, engineering graduates with varying degrees of experience and different disciplinary backgrounds, that a cluster of competencies emerge as most important (in order): teams, data analysis, problem solving and communication. They also demonstrate, from their respondents that between disciplinary backgrounds that there were significant differences. Passow and Passow (2017) demonstrate that a top tier of competencies related to transferrable skills as significantly more important for professional practice, with problem solving, communication and teamwork

Fletcher et al. (2017) surveyed and compared final year integrated Masters students and alumni with recent professional experience in the some context of those explored in this study (see Chapter 4) regarding skills most important for the workplace, based on competencies developed by the World Chemical Engineering Council (2004). They found that students placed much more emphasis on technical knowledge, but graduates with professional experience, were placed

Male et al. (2011a) reduced 64 competencies into 11 factors and explored how important these were viewed by 300 established engineers. Among the 11 factors, communication was the most critical competency required by engineers. Other, closely important competencies were transferable in nature such working in diverse teams; self-management and professionalism; with creativity/problem-solving ranked 5th. The lowest rank factor for these engineers was applying technical theory.

Table 2.1 Top 5 mean ranked competencies for practicing engineers, taken from Male et al. (2011a)

Competency as identified in questionnaire	**Mean importance**
Communicating clearly and concisely in writing (eg. writing technical documents, instructions and specifications)	4.54
Managing own communications (eg. keeping up-to-date and complete / follow up)	4.49
Managing self (eg. time, priorities, quality of output, motivation, efficiency, emotions, work-life balance and health)	4.49
Using effective verbal communication (eg. giving instructions, asking for information and listening)	4.48
Working in teams (eg. working in a manner that is consistent with working in a team, trusting and respecting other team-members, managing conflict, and building team cohesion)	4.46
Speaking and writing fluent English	4.45
Interacting with people in diverse disciplines, professions and trades	4.42
Being committed to doing your best	4.40
Solving problems (eg. defining problems, analysing problems, interpreting information, transferring concepts, integrating disciplines, thinking conceptually, evaluating alternatives and balancing trade-offs)	4.39
Demonstrating honesty (eg. admitting one's mistakes and giving directors bad news)	4.38

Male et al. (2011b) had 2542 participants rank the individual 64 competencies, it was found that, again, communication, self-management, working in diverse teams, and problem solving were most important. From the top 10 competencies (see Table 2.1), 4 communication-related competencies were among the highest ranked with a further 2 implicitly related to communication and interaction with others. This demonstrates that when we think of a skill such as communication, these can be complex and multi-faceted. And again, solving problems was highest ranked in terms of those skills that could be associated with the technical work of an engineer.

It can be concluded that, while many skills are important for professional engineering practice, the most important skills do relate to communication, teamwork, self-management and problem solving. These form the skillset which, in general, engineers value the most and rely on often to navigate and succeed in professional contexts. Often called *transferable skills*, these may also be described as “Transversal Competencies” (Care & Luo, 2016) - those skills that cut across different subject areas and are considered valuable in various contexts and necessary for holistic development, such as communication and innovation.

Such findings are found repeatedly in the literature. Across continents, it emerges that the top tier of important skills for engineers was largely transferrable, as opposed to technical, in nature. Nevertheless, the ability to deal with complexity and problem solve also remains an important aspect in relation to engineering practice.

2.3 Project-based learning

Project-based learning (PBL) and problem-based learning have been heralded as alternative and effective approaches to engineering education to improve students’ communicative and teamwork skills (Jollands et al., 2012; Mills & Treagust, 2003; Prince & Felder, 2006). To explore how engineering students shape their development with respect to these skills, it is important that there is focus on educational activities that require such skills as part of the learning process itself. Boelt et al.’s (2022) systematic review of peer-reviewed studies which measured generic competence development in problem- and project-based learning contexts found that almost all of 28 articles measured communication and teamwork skills development, which alludes to possible further justification that such types of learning activities are understood by engineering educators to have significant influence in competency development in these areas. In addition, project-based learning activities which are often group-based, offer opportunities for students to work collaboratively in, what Mercier et al. (2023) call the “intermittent development zone… [which] describes the space where between what a learner can and cannot learn without the assistance of peers” (p. 415).

2.3.1 Definitions of Project-based Learning (PBL)

Prince & Felder (2006), in their article on inductive learning methods, describe Project-based Learning (PBL) as:

> [beginning with] an assignment to carry out one or more tasks that lead to the production of a final product… The culmination of the project is normally a written and/or oral report summarising the procedure use to produce the product and presenting the outcome… (p. 130)

They also, draw comparisons between PBL and the closely related *problem*-based learning, both of which are often coalesced into a single acronym (PBL) compounding confusions between the two.

> Both normally involve teams of students in open-ended assignments that resemble challenges the students are likely to encounter as professionals, and both call for the students to formulate solution strategies and to continually re-evaluate their approach in response to outcomes of their efforts. (p.130)

Kolmos and De Graaff (2015) acknowledged this definition but also suggest that project-based learning inherently implicates a problem-orientated approach, presumably as the "assignment" is, in essence, a problem statement. Whilst recognising the similarities of Problem and Project-based learning as both entailing activity around problems- with the caveat that project problems are larger in scale and duration - they go on to differentiate the two further:

> Problem-based learning is defined by open-ended and ill-structured problems that provide a context for learning. By contrast, project-based learning is interpreted in terms of an assignment or task that the students have to perform. (p. 5)

The explanation here suggests that that while problem-based learning centers around learning as the "outcome", PBL focuses on students' actions to construct a product whether, model, prototype, report, presentation or otherwise. Similarly Savin-Baden (2007) proposes that "students are required to produce an outcome in the form of a report or design. In problem-based learning, the focus is not on this kind of outcome" and in PBL students' main drive is to "solve the problem" (p. 18).

Savin-Baden (2000) developed a multi-model definition of problem-based learning to differentiate the varying approaches based on the primary outcome which each aims to achieve. Within this framework problem-based learning was classified by intended aims to develop "epistemological competence", propositional knowledge, or "know-what". In contrast, project-based learning, was defined by goals around "professional action", procedural knowledge or "know-how". Aditomo et al. (2013) also highlight that the emphasis of learning in problem-based learning is to "acquire new knowledge", whereas PBL emphasises a focus on “practice applying knowledge”. The link for projects to engineering practice is further reinforced by the work of Dutson et al.’s (1997) review of design teaching through capstone design projects, where the aim of such project was “having students be better prepared for the *practice of engineering*” (p. 17).

From these definitions it would follow that project-based learning, owing to its outcomes-focused and practice-driven nature, can be a promising vehicle for development of those competencies that are simultaneously important for engineering practice and insufficient in engineering graduates such as communication, teamwork and problem-solving skills. Not only does PBL show potential to encourage development of interpersonal and communication skills but De Graaff & Kolmos, (2007) document that the pioneering project-led curriculum at Aalborg University in Denmark was institutionalised as a direct response to student revolts and changing industrial requirements in graduate competencies (p. 3). Aalborg University operates their entire engineering programmes under a project-orientated curriculum. These involve regular projects nested throughout engineering programmes; in the case of Aalborg university this involves approximately half of engineering degree programmes as explicit project work (Kolmos et al., 2006). Traditional teaching methods are still employed; however, projects are presented as regular opportunity for practical application of knowledge.

2.3.2 Engineering Design

Although majority of universities may not subscribe to a project-orientated curriculum like those at Aalborg, PBL has been the preferred pedagogical approach for exposing students to design in engineering education and remains standard academic practice (Dym et al., 2005; Fazelpour et al., 2024). At the same time, for many engineering disciplines, although design centric-courses may not feature frequently in the curricula, a capstone design project may nevertheless be the “only sustained design experience before entering the workforce; at a minimum, it typically represents students’ last opportunity to develop a range of skills necessary for the workplace” (Lutz & Paretti, 2017, p. 1521). Therefore, it is difficult to discuss project-based learning in engineering education contexts without acknowledging the relevance this has to engineering design.

Many definitions of design exist but limiting definitions to *engineering design*, Dym and colleague’s adopted definition is comprehensive which is the “*systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints*” (Dym et al., 2005, p. 104; Dym & Brown, 2012, p. 16). Drawing comparison to the earlier definitions of project-based learning there are clear similarities between these definitions which captures both process (or practice) and product (output).

Given this practice-centric view of engineering design, it is useful to consider what are attributes of strong designers. Dym et al. (2005), in their review of engineering design education, also highlight that characteristic for successful design are the abilities for engineering designers to: accept and navigate uncertainty; consider the wider systems context; make decisions; work in teams and communicate appropriately (p.104). These aspects cover the main design competencies, however, Razzouk and Shute (2012), also incorporate visualisation as an additional component.

Such perspectives around design have been largely accepted across institutions. Influencing this adoption is the position of many accrediting bodies, such the UK Engineering Council - the regulatory body which maintains professional standards for the engineering field across the UK. The Engineering Council is a member of the International Engineering Alliance and hence a signatory of the Washington Accord – a global treaty that ensures standards for engineering education and practice to a globally recognised requirement.

Design is deemed integral to the engineering profession and the corresponding competencies expected from graduates have been disseminated by the Engineering Council UK (2014). The Accreditation of Higher Education Programme (p. 16) guide for both educational and professional engineering institutions highlights that, regarding design, graduates must possess the ability to:

- "Understand and evaluate business, customer and user needs…
- Investigate and define the problem, identifying any constraints…
- Work with information that may be incomplete or uncertain…
- Apply advanced problem-solving skills, technical knowledge and understanding to establish rigorous and creative solutions that are fit for purpose…
- Communicate their work to technical and non-technical audiences" Engineering Council (2014, p. 16)

As an example, the Institute of Chemical Engineers (IChemE) accredits chemical engineering programmes on behalf of the ECUK and among the conditions of accreditation is a:

> …design portfolio [which] must include a major design exercise which addresses the complexity issues arising from the interaction and integration of the different parts of a process or system. It is expected that this major project will be undertaken by teams of students and that this will contribute significantly to the development of the students' transferable skills such as communication and team working. (IChemE, 2024, p. 50)

It is clear to see the parallels between the practice of engineering design and project-based learning. Both are inquiry-based; require students to work and communicate in, and beyond, design teams to make decisions to solve a problem and fulfill a, possibly hypothetical, user/clients needs, usually under conditions of significant uncertainty.

As an example design needs, Gutiérrez Ortiz et al. (2021) argue that the focus on sustainable development has introduced further complexity in the context of professional work and, hence, adds to the existing importance of students being adept at dealing with complexity through the development of relevant skills. The modern engineer must act sustainably, and to develop sustainable solutions to global and local challenges which are inherently complex and grounded in the real-world, open-ended scenarios; associated education of engineering students must incorporate this complexity through exposure to such scenarios.

By incorporating open-ended problems and activities, Gutiérrez Ortiz et al. (2021) argue that a unique type of learning occurs and that, as many of these learning experiences take place in a group-setting, teamwork and communications skills are usually developed. While the authors call for curricula to incorporate of a variety of open-ended activities throughout the entire duration of programmes, they acknowledge that:

> the capstone design project is a well-established and excellent vehicle for the practical application of programme threshold concepts in the context of an open-ended problem, and it thus represents a very useful and important exercise which connects many of the attributes developed throughout the programme. (p. 446)

Design projects are among the most established area in engineering curricula that offer students the opportunity to develop not only professional competencies discussed prior, but also skills related to navigating complex, open-ended and ill-defined problems that are challenging to frame. In Gutiérrez Ortiz et al.'s (2021) work, they provide possible approaches to incorporating such problems, and one significant example given is that of a relatively simple problem which is incrementally elaborated to include varying complexity in scope. Notably, as this example develops, it approaches a problem which mirrors those that would be encountered in a typical design project.

2.3.3 Types and Classifications of Design Projects

Often, PBL for design is incorporated as a final, summative element of engineering programmes, in the UK these would be typically named 'final year projects' whereas in the US these are commonly referred to as 'capstone projects' (Dutson et al., 1997). More recent trends, in line with the Aalborg model, have seen an increase in the incorporation of design projects in foundational years of undergraduate engineering programmes, termed *cornerstone projects* (Fazelpour et al., 2024; Freeman et al., 2016). In their review of capstone group design projects, Dutson et al. (1997) propose that capstone design projects can be defined rather vaguely as an:

> … experiential learning activity in which the analytical knowledge gained from previous courses is joined with the practice of engineering in a final, hands-on project (p. 17)

From this definition capstone projects can be understood as summative activities that are delivered to encourage assimilation of students' prior learning to address a complex, open-ended problem. Todd et al.'s (1995) survey of US engineering departments' capstone design projects in 1994 emphasised that deliveries vary substantially; however Dutson et al.'s (1997) analysis of the data demonstrated that under each category there exists a majority of programmes which were run with similar arrangements. Follow up surveys were conducted in 2005 and 2015 by Howe and colleagues (Howe, 2010; Howe et al., 2017) which found typical arrangements for capstone design projects in the US:

- working teams of students, typically from 4-6 students per team, organised according to either a pre-defined criteria or random assignment;
- involving students of the same discipline working on a general area – dubbed an "engineering program" design project by Dutson et al. (1997, p. 18)– in contrast to an interdisciplinary project;
- course duration of typically 1 or 2 academic semesters;
- projects and classes tend to run in parallel;
- run as professional simulations (as opposed to industry-led projects with direct industrial representatives being involved in the project);
- involving multiple faculty members - with up to 40:1 students to supervisor a common ratio;
- and evaluated as teams from design reports and oral presentations or design products with individual assessment usually achieved through peer-review.

Pembridge & Paretti (2010) suggest that capstone design projects bridge the "critical transition between the academic classroom and the contemporary workplace" (p15). This is substantiated by the observation of accrediting bodies for engineering disciplines have generally made capstone design projects a necessary component for undergraduate engineering programmes. This wide acceptance of capstone design projects means that research into this pedagogical activity is relevant to numerous engineering programmes.

Cornerstone projects, on the other hand serve a primary purpose of epistemological competence and professional action according to Savin-Baden's (2000, 2007) descriptions of models of problem-based learning, and these can vary in terms of extensiveness of adoption in a programme – from a single module to a foundational approach to an entire programme.

Lee (2009) developed a typology to categorise project methods into six types, according to the intent (major goals and nature) delivery (time, content, organisation, contact and resources); roles (tutor and student); and assessment and outcomes (form and focus). These six project methods were independent inquiry; independent project; guided project; directed project method; project-orientated activity; and directed activity.

Using this typology, we find that independent inquiry type fits post-graduate education and is a common feature of such programmes, it is typically related to research and conducted by individual students - the omission of project in this classification suggests Lee (2009) interprets such activities as inherently different to projects. Of particular relevance to engineering education are the independent project method which aligns with capstone design projects (Howe & Goldberg, 2019; Todd et al., 1995); and the guided and directed project methods

Table 2.2 Classification of various project methods, adapted from Lee (2009). Emphases in original.

Domain	Sub-Domain	Directed Project	Guided Project	Independent project
Intent	Major Goals	**Competent use of knowledge**, processes, decision-making and analysis/synthesis of content under supervision.	**Investigative acquisition of knowledge** and collaborative inquiry in a defined area making significant use of decision-making, synthesis and argument.	Independent **investigation and development** related to a broadly prescribed area, culminating in the production of an outcome demonstrating breadth and depth of review.
	Nature	Minor variation of process/form/topic possible but generally not open structured nor open-ended.	Defined iterative structure, but open-ended.	Open-structured, may be open-ended.
Delivery	Average time	2 - 8 weeks.	3 - 12 weeks.	6 - 12 weeks +.
	Content	Content focuses on topic and process, delivered prior to or during project development.	Some contextual content provided after issue presentation.	Focus on process and context of topic/theme, delivered prior to or during project development.
	Organisation	Individual or group projects, cooperative or collaborative.	Individual or group projects, cooperative or collaborative.	Individual or group projects as collaborative, cooperative or supportive.
	Contact	Classroom or supervisory, group/individual peer and tutor review discussions, in-class scaffolding activities and instruction.	Classroom or supervisory, group/individual peer and tutor review discussions.	Classroom or supervisory, group/individual peer and tutor review discussions, in-classscaffolding activities.
	Resources	Topic and general process materials and resources provided, students must use as directed by tutor.	Process materials, general topic materials may be provided, students should consider but may find own.	Context/topic/process materials may be provided for guidance, students decide whether to use.
Roles	Tutor	Guide/supervisor and expert on both topic and process (**instructor**). Student:	Guide/supervisor of process (**guide**).	General guide/ supervision as required (**advisor**).
	Student	Senior apprentice, **reactive learner,** independence is expected in terms of time-management, delivery of expected outcomes and choosing materials within broadly defined topic and processes.	Junior professional, **involved learner**, independent and collaborative peer learning and self-reflection, identifying learning needs and gathering appropriate knowledge within predefined processes.	Junior professional, **self-directed learner**, independent development, identifying learning needs and gathering appropriate knowledge with general support.
Assessment / Outcomes	Form	Artefact and/or supporting material showing application of prescribed knowledge to process.	Problem definitions and knowledge gained inc. verbal and written or visual presentation of process and knowledge acquisition.	Artefact and/or supporting material showing process inc. presentation, product, documentation.

Domain	Sub-Domain	Directed Project	Guided Project	Independent project
	Focus	**Utilisation** - following prescribed processes to achieve a defined form of outcome, articulation of a standard knowledge base, process and rationale.	**Investigation** - broad knowledge base and formulation of arguments through exploration of relevant fields and processes to depth in specific areas.	**Resolution** - decision-making, thorough and consistent development and articulation of a solution using appropriate processes and knowledge for the field.

would be considered linked to cornerstone design projects that would be typical throughout a degree programme (Dym et al., 2005; Freeman et al., 2016; Prince & Felder, 2006).

These three forms of project are considered inherently project methods by Lee's (2009) naming conventions, and the author draws attention to specific aspects that distinguish these. A major one is the goal, which moves from structured application and/or development of knowledge to a largely self-directed investigation to develop artefacts, which aligns with those views held by Prince and Felder (2006). The other differentiation is the roles undertaken by students and tutors. These take a view of instructor-reactive learner interactions where the direction comes largely from the tutor and moves to a learner-centric approach where the student takes ownership of their own learning (Altay, 2014). A final distinction is that of the focus of outcomes, where the motivation shifts to one of applying prescribed frameworks and culminates in self-development of frameworks in order to inform determined decisions.

2.3.4 Engineering Design Projects and Competency Development

In the same social context as presented in this thesis (see Chapter 4), Pisani and Haw (2023) demonstrated, unsurprisingly, that final year chemical engineering undergraduate students generally associated higher levels of critical thinking and high levels of agency with open-ended group projects.

Fletcher and Harrington (2018) surveyed chemical engineering undergraduate students, again in the same context as outlined in Chapter 4, on their perceptions of skills before and after a major capstone design project experience. The skills included were of three main categories communication skills (verbal communication, written communication, oral presentations, minute taking and listening), personal effectiveness (time management, project management, leadership, decision making and working with others) and research skills (word processing, data analysis, IT and research of literature). They find that many transferable skills see some improvements through students' experience of design. It is evident that, following this design project, students on-average self-assess skills related to communication higher in competence. In contrast, before this experience, many personal effectiveness skills are ranked with high confidence. On average, most skills analysed demonstrated some positive shifts in self-perceptions of skills competence and demonstrates that the design experience may have contributed to students' development of professional identity. Perhaps, unsurprising, those aspects which are assessed explicitly observe among the greatest improvements in terms of students self-ranking. The survey, while demonstrating the there are changes in perceptions related to these skills, does not fully explore how students' understanding of these skills develop and what specific experiences with the design experience contribute most these developed understandings.

In a study of mechanical engineering students on three different projects, including a group capstone design project, Picard et al. (2022) found that the most commonly reported non-technical learnings were communication; organisation; time management and division of labour. Respondents were also asked to state the two most significant challenges faced, along with whether they were able to develop skills to manage those challenges in the future. They found that the most responded developed skills related to challenges faced were (in order) technical design methodologies, time management, division of labour and teamwork skills. Similar to the work of Fletcher & Harrington (2018), they found that the self-perceptions of a set of skills surveyed before and after, demonstrated that time management and interprofessional competence observed statistically significant improvements.

Lutz and Paretti (2017) explored the scope of learning, including "tangible and intangible outcomes" (p. 1522), developed through students' perceptions of capstone design projects. They conducted semi-structured interviews with students from three institutions undertaking, or having just undertaken, capstone design projects in mechanical, general and chemical engineering. Guided by questions primarily centred around the role of mentors and learning developed, but also the most significant challenge faced by students on their projects, four themes emerged of students learning on capstone design through their qualitative thematic analysis: engineering design; teamwork and communication; self-directed learning; and engineering identity.

On the other hand, Singer et al. (2024) explored a general engineering cornerstone design project from a thematic analysis perspective. They found a similar set of themes as Lutz and Paretti, (2017) (personal/professional attributes such as communication, teamwork, problem solving and creativity) but in addition also included design thinking and sustainability. This demonstrates the emphasis on *epistemological competence* (Savin-Baden, 2000) generally found in which tends to be among the intended learning outcomes for pre-capstone projects.

2.4 Engineering Identity Formation

Despite a shift to outcomes-based engineering education, graduates are still ill-equipped with respect to critical professional skills. Competency "mapping" and addressing competency "gaps" is a narrow view of competency development and tends to ignore the role of the individual. The work of Walther and colleagues (Walther et al., 2011; Walther & Radcliffe, 2007) has demonstrated that individual competency formation is an inherently complex and deeply social process. They suggest that competency is not merely developed through explicit, targeted instruction, but through aspects "surrounding the formal education process" (p. 45). They refer to these knowledge, skills and attitudes that develop through these often-unintentional factors as "Accidental Competencies". Educators have been long aware of such aspects of the educational experience with the notion of the Snyder's (1971) *hidden curriculum* and Miller & Parlett's (1974) *examination game* being notable examples. Walther et al. (2011) cite Scott and Yates (2002) who recognise that skills can, and are, impacted by "the whole range of formal and informal experience encountered while at university." (p.372).

The results of Walther et al.'s (2011) analysis of focus groups of final year and recently graduated engineering students across four institutions yielded seven competency clusters that informed their professional identity: flexibility and creativity, interaction, plan, professional realities, self, social context, and technical. Among the most frequently reported reflections were those categorised into flexibility and creativity. Interaction and social context overlapped somewhat but the former involved transmission of information, whereas the latter captured the relation aspect of educational and workplace settings.

Ultimately, Walther et al. (2011) demonstrates that professional formation is complex and an outcomes-based assessment of competency lacks consideration of such complexity and is "limited in its capacity to capture all aspects of engineering learning…" (p. 706) and that "a wide range of educational factors interact in a complex fashion to impact students on the level of both specific learning outcomes and intangible, attitudinal aspects." (p.706). This is strikingly similar to Dannels (2000), who states that "the professionalizing process in the classroom is laden with situated, context-based complications" (p. 8). Such interpretations reformulate engineering education as an inherently social learning system and demonstrates that educators must be aware of, and consider how, social aspects of the learning experience, that may be otherwise incidental, do impact students' competency and professional development.

Meyers et al. (2012) developed 30 qualities that inform students professional engineering identity which were put forward to survey participants comprised of engineering students at a single North American institution for confirmation of those qualities' relevance to their engineering identity formation. More than 90% of respondents (n = 701) agreed that, in order of most agreed, "being able to make competent design decisions; being able to work with others by sharing ideas; accepting responsibility for the consequences of actions; speaking/communicating using accurate technical terminology" (p. 125) were the most significant factors informing respondents' self-identification as engineers.

Lowe et al. (2022) adopted a situated learning theory perspective (Lave & Wenger, 1991) that emphasises the impact that social contexts have on learning. They hypothesised that professional identity formation is associated with significant exposure to professional practices. To explore this they analysed students' "activity claims" (written submissions) as part of a “Professional Engagement Program” that spanned across a degree programme. These activity claims were analysed and coded against several taxonomies. These included:

- Engineers Australia (2013) stage one competencies, which captured various knowledge & skills, engineering application abilities, and professional and personal attributes
- Anderson & Krathwohl’s (2001) revised Bloom’s Taxonomy which captured remembering, understanding, applying, analysing, evaluating, and creating.
- Maton’s (2013) Legitimation Code Theory which captures activity types on an epistemic plane where phenomena are classified according to both how well- or ill-defined they are and how standardised or open-ended approaches are for dealing with those phenomena

Their comprehensive analysis of activity claims suggests that projects in the authors’ context, including those industrially based, research or design-related, were unsurprisingly associated with significantly more reflections relating to higher-order levels int the revised Bloom’s Taxonomy, especially around creating. With respect to the Engineers Australia stage one competencies, the same projects were associated with greater reflections on teamwork skills, but only engineering research projects invoked greater reflection on communication skills. Unsurprisingly, with respect to Legitimation Code Theory, the authors’ group several activities as ‘design projects’, and position these as undefined phenomena that involve open-ended approaches on the epistemic plane. Lowe et al. (2022) conclude their work with a recognition that their analyses points to the importance of developing students’ abilities in handling complexities, and they suggest design projects as vehicle for such development.

A deeper understanding of the social surroundings and their impact provides educators with a more nuanced understanding of how best to develop competencies, as well as a greater appreciation of the fundamental role that interactions have in influencing development and engineering identity formation. For example, Stevens et al. (2008) demonstrates this with a four-year longitudinal ethnographic study of engineering students. Their work shows that various factors impacting engineering identities are complex, situated and difficult to predict; but nevertheless, offer insights into such processes that cannot be necessarily obtained through pre-determined competency investigations.

2.5 Situated Contexts: Qualitative Inquiry in Engineering Design Projects

There are many theoretical lenses with which engineering education and learning can be understood. These can be generally classified as either behaviourist, cognitivist, and situated (Newstetter & Svinicki, 2014). Where much of the discussions around competencies and outcomes-based learning is informed with behaviourist and cognitivist perspectives, Johri and colleagues (Johri et al., 2014; Johri & Olds, 2011) demonstrate that situated frameworks offer a holistic perspective than the dominant cognitivist models for approaching engineering education research where learning is understood “as situated in a complex web of social organization rather than as a shift in mental structures of a learner” (Johri et al., 2014, p. 49)

Unlike cognitivism which classifies knowledge as distinct, mental models within individuals, central to situative theories is the view that knowledge is distributed in the world, where individuals act and interact using artifacts to mediate their action-interaction. Through participation within communities of practice (Lave & Wenger, 1991) or activity systems (Engeström, 1987), learners migrate to becoming “outsiders” to members of such communities and therefore “learning involves the construction of identities” (Lave & Wenger, 1991, p. 53).

It is important to note that Lave (2008) reflects that their original theory of situated learning did not postulate that such communities, and the process of becoming members, were uniform or constant - rather these were presented as “contradictory, shaping, and shaped by differences and constitutive tensions among changing persons, activities, and circumstances” (p. 289).

The above perspective paints a complex, evolving view of the process of learning and communities of learners and practitioners. Johri and Olds (2011) suggest that situativity has direct implications for engineering education research and these include, among others, the need for empirical studies of: teamwork and collaboration; role of interactions, including peer and informal learning; and situated identities and conflict between identities. To develop understanding of how engineering students navigate project-based learning in the context of design, it is necessary to go beyond quantitative research approaches (or even simple survey design) and move towards qualitative inquiry which incorporates in-depth, interpretive methods to investigate the nuances of individual experience. In the context of engineering education research, there are limited studies in project-based learning utilising such approaches.

In their synthesis of literature to present a model of contextual factors which contribute to learning, Tessmer and Richey (1997), demonstrate that learning is not merely decontextualised acquisition of knowledge or skills. Rather, they emphasise different conceptualisations of context from the orientating context to the instructional context to the transfer context. The wider literature presented around competency largely concerns itself with the transfer context (the "gaps" in competency) and the instructional context (which, where pre-/post-survey competency research is concerned, primarily observes students’ developments as a black box). There is limited research which explores the instructional contexts in a rich, descriptive manner, and more so limited research in the orientating contexts, those assumptions, belief and experiences that learners carry into learning activities, which have significant impact on a given educational experience.

Tessmer and Richey (1997) highlight some significant concerns around the importance of context when considering instructional design. After all, as they state, "we are condemned to context" (p.4) and the influence of context has on a given learning activity depends on the learner's characteristics, the subject matter, and the strength of the contextual factors. Their view of contexts (orientating, instructional and transfer) demonstrates the breadth of factors involved, however among these are aspects which relate well with the findings presented.

Such perspectives would aid in more detailed exploration of the widely held belief by engineering educators involved in, specifically capstone, design: that such activities aim to achieve three fundamental outcomes: 1) for students to assimilate prior learning, 2) deal with complexity arising from open-ended projects, and 3) to simulate the workplace (Pembridge & Paretti, 2010). In their review of approaches to deliveries of design Dutson et al. (1997) conclude their study with the following statement:

> Although the individual structures of capstone design courses are extremely diverse, the objective of nearly all such courses is to provide students with a real-life engineering design experience. Other objectives often include the development of interpersonal and communication skills [and] enhancement of student confidence… (p. 25)

The expectations of “simulation” and “real-life engineering” within design practice is laden with assumptions and central to how both faculty and students understand, and navigate, design projects. For example, the work of Dannels (2000, 2003) and Paretti (2008) demonstrate that such notions around attempted simulation of a workplace may have unintended, or even, detrimental consequences to students’ learning - as ultimately, these are two competing activity systems.

Dannels (2000) explored through qualitative inquiry, how mechanical engineering students’ understandings of the academic and professional contexts shaped their professional identities as the undertook a capstone design project. Significant in the findings was that it emerged that academic context often governs this formation of identity. Students observed and interviewed in Dannels (2000) study prioritised academic audiences, namely instructors and the associated academic objectives, in order to navigate their capstone design project. This is evidenced in an excerpt:

> Deanna [Dannels]: So, why don’t you talk with actual customers, or your client, or members of industry who could help?
>
> Marcus: Why would I? That wouldn’t help me in school; they are all somewhere else. (p. 21)

Fundamentally, the student took a pragmatic approach and conceptualises the task, and associated actors involved, as an academic one and not professional. Highlighted in the excerpt is the social context and the lack of visibility of professional participants in the design. Similarly, the ultimate aim of the task was also reframed by multiple interviewed students:

> Ian: That's right, we want a good grade here, but a good grade doesn't really mean a good design. … you've been asking why we don't talk to customers but you know we are not graded on that. We are graded on the end result. And really we are graded on whether we get along with our adviser. We do what have to get a good grade. (p. 23)

The academic objective of attaining "good grades" directs much of students' behaviours and decisions, despite the design task involving the design of an "actual product for industry… for actual clients in industry" (p. 10) and would be subsequently implemented. This demonstrates the prevalence of academic factors and the way students use these factors as tools to mediate their actions and interactions in a design task. This demonstrates that when design projects involve active engagement with industrial partners, or even where there is a concerted effort from instructors to simulate a professional settings such as those papers described in Lavado-Anguera et al.'s (2024) systematic review, the situated academic context nevertheless influences students decision-making and socially-informed practices.

In a follow-up to this work, Dannels (2003) utilised situated learning and activity theory perspectives to explore communication practices of engineering students as components of capstone design presentations. Dannels grouped three instances of tensions that arose where students were simultaneously expected to address a workplace need and academic need, which were contradictory. First, in the context of audience types and needs of audiences the academic context involved technical complexity whereas the professional context called for simple, followable communication practices. Second, Identities were also reconsidered in light of the two activity systems; participants were simultaneously students but also expected to act with, or roleplay, professionalism. Third, the academic context also required a structured-process orientated retelling of design, whereas the workplace calls for problem-orientated discussions, where the central problem justifies the final design. Dannels notes that for both the first and second tensions, there is a strong deference to academic activity systems (norms and practices); whereas for the third there was more variability – with faculty recognising that defined steps in a design process "isn't really how it works out there" (p. 161).

Similarly, Paretti et al. (2008) explicitly utilises a situated learning and activity theory perspective to explore capstone design, through the specific lens of communication practices and communication assignments that design tends to be centred upon; with the authors emphasising that writing, for example, as inherently situated. Activity theory views communicative "texts" in various formats (reports, presentations etc.) as mediating artifacts. Such artifacts were viewed with differing utility for student participants – Paretti (2008) note that notebooks and progress reports, were required for grading purposes but lacked "relevant information mediating the management and conduct of a workplace-oriented design project" (p. 498). Paretti demonstrates the significant subjectivity of experience across the projects by demonstrating case studies of two observed teams, one that "rebelled" against the academic activity system and perceived busywork, refusing to engage with, what they interpreted as, unnecessary busywork and another team that valued the instructors academic-orientated comments. The latter deferred to the academic context, despite persisting tensions.

All of these studies underscore Walther et al.'s (2011) comments around how formal and informal educational factors influence attitudinal aspects. Context is pivotal for understanding what goes on in a given educational experience, including design projects. Nevertheless, there remains a limited qualitative exploration of longer, sustained design projects within engineering education and how social aspects related to these unfold (Mercier et al., 2023).

2.6 Summary

This chapter situates the thesis within the broader academic discourse, aligning with the Grounded Theory (GT) approach and an agnostic stance on existing literature, as outlined in Chapters 3 and 4. Consequently, the literature review did not inform data collection or analysis but was conducted primarily after the analysis of primary data. The chapter began by examining key engineering graduate competencies and associated competency gaps. It then argued that project-based learning and engineering design frequently intersect and serve as effective pedagogical approaches for developing these competencies. Beyond competency mapping, the discussion advances towards a more nuanced understanding of engineering identity formation. Finally, the chapter explored situative perspectives in engineering education research, emphasising the significance of qualitative, context-specific investigations into engineering design projects.

Chapter 3. Methodological Considerations

3.1 Introduction

This chapter clarifies the philosophical and methodological positioning of the study, and the basis from which the methods used were adopted. Prior to addressing these aspects, a process-orientated quality framework for qualitative inquiry in engineering education research is introduced. After a brief justification for researcher reflexivity in qualitative inquiry, the epistemological stance, constructionism, is then defined. Thereafter, the interpretivist theoretical perspective of symbolic interactionism, and its relevance to the presented work, is formulated. The methodological approach of Grounded Theory, its various manifestations and implications for qualitative research methods are analysed in detail, beginning with addressing the notion of quality of the developed grounded theory and approaches to data collection and analysis. Finally, a reflexive account of the researcher's methodological development is presented.

Reflexive Commentary

Throughout the discussion of these qualitative research considerations, I present reflexive statements, which clarify my positions adopted in this study, and how these positions address the process-orientated quality framework initially introduced. Readers may note shifts from third person to first person when such reflexive statements are made throughout the chapter, and these are made clear through appropriate formatting, such as this paragraph. This was a deliberate narrative choice to underscore the inherently self-reflective nature of explicating one's beliefs and assumptions informing their interpretations – to speak in the third person for such statements would attempt to present myself as an objective entity which stands apart from this qualitative endeavour, which I believe would be incongruous with my epistemological stance (discussed later).

3.2 Quality of Qualitative Inquiry in Engineering Education Research

In their analysis of methodologies reported in articles published by the European Journal of Engineering Education (EJEE), Malmi et al. (2018) concluded that, while accepted submissions had clear research aims, analytical techniques were underdeveloped with most qualitative studies either lacking significant methodological rigour or including no discussion at all. Koro-Ljungberg and Douglas (2008), in their empirical investigation of qualitative studies published in the Journal of Engineering Education (JEE), reached similar conclusions; that few qualitative studies were published but those that were lacked epistemological consistency.

These reviews of research published by two major engineering education research journals agree that the majority of Engineering Education Research (EER) studies remain quantitative in nature; and, while calling for more “elaborate methods” (Malmi et al., 2018) to address the challenges in engineering education, an emphasis must be placed on methodological quality.

Aware of the general unfamiliarity of interpretive methods among engineering researchers, Walther et al. (2013, 2017) developed and explored a process-orientated quality framework for practitioners' consideration when formulating and conducting qualitative inquiry in the context of EER. Their framework includes five data-focused validation criteria, which apply to the qualitative research endeavour. The framework is elaborated through the primary lenses of "making data" and "handling data" but also includes process reliability, which supports these validation constructs. The elements of their quality framework are summarised in Table 3.1.

Reflexive Commentary

These validation constructs are explained and referred to at relevant points in the proceeding work. Through reflexive reference of the validation construct in the discussion of methods, it is hoped that ethical validation, as described in Table 3.1, is promoted. Reflexivity is appropriate for the communicative conventions of, and demonstrates responsibility towards, the qualitative research community. By conveying my intentions, interests, preconceptions, and development, it is hoped the research community can gauge the impact these aspects have had on the research study.

3.3 Reflexivity and Assumptions

In the methodological handbook *Interpreting Qualitative Research*, David Silverman (2015) states: "I have lost count of the run of the mill qualitative research papers I have come across which find it necessary to define their work in terms of obscure philosophical positions... you do not need to understand these terms in order to carry out good qualitative research" (p. 7). While this assertion may be posited for practical advice, validation of qualitative research according to Creswell & Miller (2000), "requires thinking beyond specific procedures- to acknowledge the lens being employed in a study and the paradigm assumptions of the researcher" (p. 129). The beliefs held by the investigator have a fundamental influence on how studies are formulated and carried out, irrespective of the researchers' reflexive awareness of these. The research questions constructed; data collected; analytic approaches employed; and findings communicated - the underlying beliefs and assumptions permeate the entire research process. Therefore, if it is to be considered reliable, qualitative research necessitates reflexivity, which includes the investigator situating the work on clear epistemological and theoretical foundations (Case & Light, 2011; Walther et al., 2013). The epistemology, theoretical perspective, methodology and methods underlying this work are summarised in Figure 3.1.

Table 3.1 Validation criteria and associated relevance to research process adapted from Walther et al. (2013, 2017)

Criteria	**Relevance to Research Process**	**Focus**	
		Data Making	**Data Handling**
Theoretical Validation	Fit between social reality under investigation and theory generated	The research process needs to be able to capture the full extent of the social reality studied.	Interpretations need to reflect the coherence and complexity of the social reality under investigation.
Procedural Validation	Features of research design that improve theoretical validation	Implementation of strategies in the research design to mitigate threats to contextual validation (e.g. researcher bias, biased sampling.	Mitigation of risks in mis-constructing participants' reality in the researcher's interpretations.
Communicative Validation	Integrity of social construction with relevant communication communities	The data gathering needs to capture the respondents' inter-subjective reality.	Abstract interpretations are grounded in participants' accounts. Knowledge produced must be represented with meaning conventions of the research community.
Pragmatic Validation	Compatibility of theoretical constructs with empirical reality	The sensitising concepts underlying the research design need to be compatible with reality in the field.	The knowledge produced needs to be meaningful in the social context under investigation.
Ethical Validation	Aspects of integrity and responsibility	The research design, methodological choices and interpretations must do justice to participants accounts.	The methodological choices and dissemination must do justice to the stakeholders in the research.
Process Reliability	Mitigation of random influences on the research process	The data needs to be collected and recorded in a dependable way.	Procedures for generating and representing knowledge need to be established and documented.

3.4 Epistemology: Social Constructionism

Objectivist-orientated epistemologies give rise to positivist (and post-positivist) theoretical perspectives with which the goal of the social research is to uncover generalizable laws that explain the observed social phenomenon, detached from the context from which it arises. Interpretivist theoretical perspectives, on the other hand, emerge from either constructionist or subjectivist understandings of the social world.

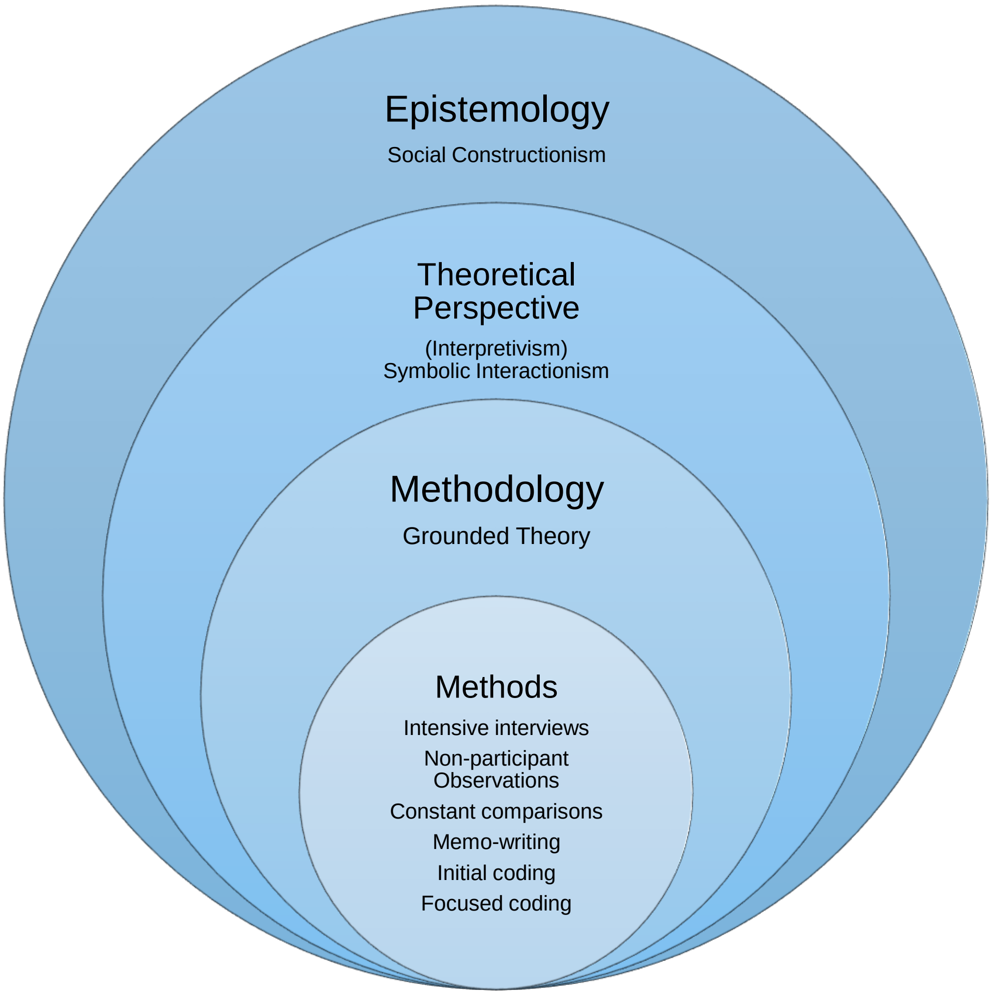

Figure 3.1 Summary of epistemological, theoretical, methodological position of study and methods employed

Constructionism, or more fully - social constructionism, is the epistemological position that underpins this work. For the definition of constructionism, with respect to this work, Crotty (1998) can be referred to: "the view that all knowledge, and therefore all meaningful reality as such, is contingent upon human practices, being constructed in and out of interaction between human beings and their world, and developed and transmitted within an essentially social context" (p. 42). This stands apart from subjectivism (that there is no external reality) and relativism (that any representation of reality is valid), both of which are problematic positions with which to conduct coherent qualitative inquiry (Bryant & Charmaz, 2010). As this work is an exploration of students' understanding of, and engagement with, the design project experience - an inherently social, complex and evolving phenomenon involving participants, both peers and academic staff - the constructionist epistemology is particularly relevant.

3.5 Theoretical Framework: Symbolic Interactionism

Interpretivism is a theoretical perspective where the researcher engages with participants to grasp the subjective meanings of social phenomenon under study, which are situated meaningfully in a particular context. The aim of an interpretivist study is "to understand a community in terms of the actions and interaction of the participants, from their own perspectives" (Tobin, 1999, p. 487). The interpretivist observes social phenomena as processes under continual development through social interactions (Bryman, 2012), following the constructionist epistemology. This work is then an interpretation based on the participants' actions and observed interactions, and it is agreed that such research "sacrifices an element of objectivity in order to obtain situated meaning-making" (Bryman, 2012, p. 552). As such, it is then understood that the findings and conclusions reached are not presented with an exclusive claim to truth, and other researchers may have reached different, yet valid, interpretations. The particular interpretivist paradigm employed within this study is Symbolic Interactionism, the pragmatic theory to which the Grounded Theory Method traces its roots (Bryant & Charmaz, 2010; Crotty, 1998).

Symbolic interactionism (SI) is a theoretical framework with which "small-scale phenomena associated with everyday life" can be understood and is founded upon the works of pragmatists such as George Herbert Mead (Ritzer & Stepnisky, 2017). The term 'symbolic interactionism' was coined by Blumer (1969), a student of Mead's, who describes SI as a "methodological position" (p. 1), or a "framework of study and analysis" (p. 6), meaning a theoretical perspective which informs this study (Crotty, 1998). Blumer (1969) presents three main premises upon which SI is founded upon.

1. Human beings act toward objects (e.g. physical, social or abstract) on the basis of the meanings that the objects have for them.
2. The meanings of objects come about by social interactions with associates.
3. The meanings are dealt with, and subjected to modification, through an interpretive process.

Reflexive Commentary

These three premises inform the grounded theory methodology adopted in this study. With reference to the presented work, I found the first premise was evident as I understood participants to be social actors, whose actions and interactions were indicators for the conceptual meanings held by them as individuals, collectives and groups about their lived social phenomena. The second premise, with which I agree, signifies that the participants are understood to develop meanings, which are socially constructed, and that shared meanings are indicative of social understanding (Blumer, 1969). The final premise asserts that meanings are understood as revisable and situated in a particular context. This theoretical perspective simultaneously acts as methodological orientation and as a lens with which the resulting analysis can be understood. Hence, in this work I aim to present "limited, tentative generalizations, not universal statements" of the area of study (Bryant & Charmaz, 2010, p. 31). Further, theoretical concepts from symbolic interactionism (e.g. action, meaning, process etc.) act as sensitizing concepts which facilitate initial analyses of observations and data collected (Charmaz, 2014).

3.6 Methodology: Grounded Theory Method

3.6.1 Introduction to the Grounded Theory Method

The Grounded Theory Method, hereafter referred to simply as Grounded Theory (GT), emerged from qualitative nursing health research on terminally-ill patients conducted by Glaser & Strauss (1967). This work was considered revolutionary for its time; with the authors arguing that theory in sociological work remained in the hands of a few “grand theorists”. Further, Glaser & Strauss (1967) highlighted the forcing of such theory upon data was common practice in sociological studies with little focus on empirical studies –indeed, disparity between empirical evidence and theory was dismissed, attributing the cause to ‘bad data’.

Glaser (1998), coming from the Columbia School of statistical research, recognised that most quantitative survey research involved *a priori* assumptions and some involved a preceding stage of qualitative interviews. Researchers needed to know which questions were relevant prior to delivering surveys and questionnaires. He recognised that this stage served as a generative stage for hypotheses prior to testing; however, this crucial stage in statistical social research was given little importance despite it serving a fundamental function and influence in the proceeding study. Glaser & Strauss (1967) argue that these are two distinct approaches, *generating* and *verifying*, and each require different approaches. Strauss, influenced by pragmatist and Chicago school interactionism, which has been discussed under 3.5, brought notions of action and interaction and the process of interpretation to the method – although these were unaddressed in the original work (Strauss & Corbin, 1990). Studies on verification being well-established, GT was developed to address the methodological gap present in generating empirically founded theory by focusing on appropriate processes, methods and techniques (Kenny & Fourie, 2014).

Glaser & Strauss (1967) identified that generating theoretical hypotheses of social phenomena must be divorced from preconceptions and biases that researchers may bring to the study. GT advocates that hypotheses must be empirically induced from data and, hence, the resulting theory is *grounded in data*. In his later works, Glaser (1992) went on to emphasise the admonition of 'forcing' one's biases upon data and protection of 'emergence' of theory when employing GT.

There have emerged three dominant variants of the GT method since its inception – Classic (or Glaserian), Straussian and Constructivist. The differences between these approaches are focused on the peripheries of the method itself. Straussian GT employs more 'prescriptive' approaches than Classic GT according to Glaser (1992). Constructivist GT, however, is a reinterpretation of the method considering primarily epistemological developments emerging in qualitative research discourse which were considered unaddressed by prior manifestations of GT (Bryant & Charmaz, 2010). Despite these differences, most of the core procedures, including constant comparison, theoretical sampling and memo-writing, are employed by all variants of GT.

3.6.2 Criteria for Quality for GT: Fit, Work, Relevance and Modifiability

Glaser & Strauss (1967) begin the discussion in their seminal work on grounded theory with a criterion for quality of sociological theory, which they suppose the GT method addresses: "…such a theory fits empirical situations, and is understandable to sociologists and laymen alike. Most important, it works – provides us with relevant predictions, explanations, interpretations and applications." (p. 1)

Glaser (1978) elaborates upon these three interlinked elements of theoretical quality – *fit*, *work* and *relevance* – as well as introducing another, *modifiability*; which Charmaz (2014) recognises as useful for evaluating grounded theory studies.

Theoretical *fit* is determined from how well theory aligns with empirical findings. The method itself, as has been mentioned above, addresses this by developing theory inductively from data. It is the *fit* of theory to data, which subsumes the three other criteria for quality: work, relevance and modifiability.

The criterion of *work* suggests that theory must have predictive and explanatory capability. Thus, much research in social science research may meet the criteria of *fit* especially in the case of descriptive ethnomethodological studies, however, the criteria of *work* suggests a theory must centre upon sufficiently abstract concepts, which have analytical reach beyond the particular context from which it was developed (Charmaz, 2014; Glaser, 1992; Strauss & Corbin, 1990).

The criterion of *relevance* means that theory must be relevant to formal social research and especially to the practitioners in the substantive area from which it emerged. Glaser & Strauss (1967) argue that although social theory may possess great analytical reach, if it is divorced from pragmatic value to practitioners, especially in the substantive area from which it emerged, then it neglects this requirement. Again, theoretical *fit* prevents analytical findings from becoming separated from the empirical context.

Since the primary criterion for quality is *fit*, proposed theories must maintain this criterion by introduction of new and unexplained data. Hence, to ensure tentative theory does not manipulate new data, the theory must be *modifiable*. Theory emerging from inductive grounded theory methods is never ‘complete’ in an absolute or final sense, and developed theory is subject to continuous development. *Modifiability* is inherent in the process of doing GT work with theoretical claims being developed and validated by new data that is collected and analysed.

Apparent in this discussion of the quality criteria of grounded theory is the close agreement with the quality criterion of theoretical validation proposed by Walther et al. (Walther et al., 2013, 2017) presented earlier. This is an important connection as Walther et al. (2013) suggest that theoretical validation is foundational in qualitative research, and that it is from this type of validation that the “other constructs can be understood as contributing to theoretical validation” (p. 631). The notions of *work* and *relevance* pertain to the pragmatic criterion as these indicate the utility and resonance of the developed theory respectively.

3.6.3 Literature Reviewing & Theoretical Agnosticism

One way to prevent the propagation of biases was to eliminate these in the first instance, hence the GT method initially cautioned against extensive review of the literature prior to conducting qualitative research.

> An effective strategy is, at first, literally to ignore the literature of theory and fact on the area under study, in order to assure that the emergence of categories will not be contaminated by concepts more suited to different areas. (Glaser & Strauss, 1967, p. 37)

Since this early methodological position, Corbin & Strauss (1990) loosened their stance on this, suggesting that the literature is a good point from which to base some preliminary questions, which has been met with agreement from more recent GT proponents (Charmaz, 2014); however, Glaser with his objectivist leaning, responded to these initial deviations by reaffirming his stance around this prohibition (1992). Regardless, all GT variants agree that prior study of theoretical and conceptual frameworks, which come to underpin the proceeding study, should be reviewed critically and effort should be expended to suspend preconceived notions of what is expected in the social reality under consideration.

Increasing engagement with literature occurs as the emerging theory becomes well formed; hence, reviewing the literature is relegated to the closing stages of research, as a new source of data. By utilising the extant literature as further data, researchers strengthen their inductively generated hypotheses and theoretical claims by connecting to the wider literature.

Reflexive Commentary

Prior to the selection of the grounded theory approach, I reviewed the literature surrounding communication theories in the context of engineering design projects, motivated by earlier studies I had contributed to (Fletcher et al., 2017). Although, these provided interesting theoretical positions and implications, I found these to be divorced from my own experience of CE design, prompting me on a search for more inductive inquiry. Upon reflection, I found the works to be too abstract and theoretical without much relevance to what I experienced myself and my interactions with others who undertook the CE design too. While the literature reviewed at this early stage is still referenced in this work primarily for setting the context, it was treated with the critical stance of "theoretical agnosticism" introduced by Henwood & Pigeon (2003 p. 138) and supported by Charmaz (2014). This stance declares that the 'researcher as tabula rasa' urged by Glaser is a defective principle (Urquhart, 2002), and instead views prior theoretical constructs as useful sensitizing tools and for facilitation of constructing research questions. In addition, this view treats developing theoretical claims through the study with scepticism and reservation, which adds to the rigour of the method. This position addresses communicative validation in Walther et al.'s (2017) framework, by addressing the co-construction of interpretive meaning with the research community by generating meaning from the literature as a data source.

3.6.4 Data Collection

Characteristic to the GT method, data collection permeates through the research process. Data collected may include observations, extant texts, interviews and, eventually, reviewing the literature as a source for further data. This exemplifies what is meant by the classic GT dictum that "all is data" (Glaser, 1978, 1992).

Data collection and data analysis proceed in an iterative cycle throughout the GT process (Charmaz, 2014). Data collection is followed by analytical techniques to elucidate 'what is going on in the data' and this process feeds back into and informs the analyst for further data collection (discussed under section 3.6.5.2). Iterative data collection and analysis is particularly significant for GT research, in fact the title, Grounded Theory, can be explained more fully as the "emergence of *theory* that is *grounded* upon data".

3.6.5 Data Analysis – The Coding Process

Main individual techniques employed for data analysis have become contested following the methodological split between Glaser & Strauss, and the introduction of Charmaz's constructivist reinterpretation of the method (Kenny & Fourie, 2014). Despite these differences, the primary process through which data is analysed is through *constant comparison*. Constant comparison is such a fundamental and foundational process of data analysis and collection in GT that the original collaborators deliberated over naming the approach the *constant comparative method* (Glaser & Strauss, 1967). The centrality and utilisation of constant comparison throughout analysis is apparent when the coding process is considered.

Coding is understood to be the analytic interpretation of data through the development of a concept or word (code), which aims to develop a social understanding of the phenomena observed. In GT, constant comparisons move the coding process beyond mere recapitulation of observations and towards a synthesised analytic understanding, across indicators.

In the constructionist GT approach undertaken herein, the general coding approach involves two key stages: *initial* and *focused* coding. To code substantively, a researcher first codes in an *open* manner, allowing for analytical concepts and paths to emerge, followed by a stage of *selective* or *focused* coding, at which point the initial codes are compared to develop significant or focused concepts with which large batches of data can be examined (Charmaz, 2014).

The constant comparative method contributes to the procedural validation of handling data (Walther et al., 2013). Through constant comparison of data, incidents and concepts; the researcher's analyses both remain close to the participants' reality and ensure that theoretical claims are treated sceptically until participants' accounts are addressed by such claims.

3.6.5.1 Initial Coding

Initial coding involves analysing the data, at first, line-by-line while remaining close to the data to prevent forcing theoretical biases upon the data. Charmaz (2014) suggests that the coding here should make use of gerund (the noun forms of verbs):

> Think of the difference in imagery between the following gerunds and their noun forms: describing versus description, stating versus statement, and leading versus leader. We gain a strong sense of action and sequence with gerunds. The nouns turn these actions into topics. (p. 121)

From this analysis, a list of tentative indicators (of data) emerges and, by grouping and comparing these, a concept is developed. Once concepts emerge, indicators are continually compared with indicators and with the tentative concept – this has the dual purpose of further conceptual elaboration and testing of the data.

Another technique employed at this stage is the utilisation of incident-by-incident comparison, which assists the researcher in developing the properties and dimensions of evolving concepts (Wuetherick, 2010). Throughout the open coding procedure, the researcher elicits analytical inductions by posing questions to the data:

> “What is this data a study of?" "What category does this incident indicate?" "What is actually happening in the data?" "What is the main concern being faced by the participants?" and "What accounts for the continual resolving of this concern?" (Glaser, 1998, p. 140)

The utility of these questions in forming the basis for core conceptual categories identified has been supported by Charmaz (2014). The characteristic aspect of this stage of coding is for the researcher to remain open to conceptual paths in the data. This aspect of being open to multiple interpretations for the data to inform analysis is a technique that GT asserts to ensure a fit is achieved with the empirical reality under investigation. However, once concepts begin to emerge it is the job of the researcher to *theoretically saturate* these concepts by utilising *theoretical sampling*.

3.6.5.2 Theoretical Sampling

Sampling in GT is directed by the criteria of *fit* and *relevance*. *Theoretical sampling* informs guided data collection to mirror what is relevant to the field of study, that is, what the researcher has become theoretically sensitive to, as the research continues. The primary function of theoretical sampling is to purposively sample to address gaps in the theory that have not been addressed by the data. Sampling in such a way acts as a means for conceptual elaboration, that is, to utilise the tentative theory to form abductions to obtain the range of theoretical possibilities and ground these in data (Charmaz, 2014). This form of sampling also provides a check upon the theory and opportunity to examine the tentative inductively generated hypotheses. Theoretical sampling ultimately attempts to capture variation (Charmaz, 2014) and, by this process, categories become theoretically saturated. Theoretical saturation can be described as the point at which new data does not modify the developed theory in a significant fashion.

Taken together, the coding and theoretical sampling processes give rise to an inductive-abductive logic, which permeates the GT research process. The coding process involves inductive inferences in the generation of hypotheses and then, remaining theoretically agnostic, the researcher develops abductive theoretical explanations and tests these with new data through theoretical sampling (Charmaz, 2014). This inductive-abductive reasoning involved in grounded theory research addresses the concerns related to theoretical validation when handling data in quality framework proposed by Walther et al. (2013, 2017).

3.6.5.3 Focused Coding

Transitioning into *focused coding* involves the researcher focusing efforts towards a category that has emerged as the core phenomenon of the study. Glaser identifies several criteria by which a core category is determined, including centrality or relatedness to conceptual categories; frequent reoccurrence in data; and longer duration to reach theoretical saturation.

It as it this point that the core category and those variables that are of relevance to this category are selected according to the above criteria. Theoretical sampling is then utilised to seek evidence of the core variable in the data, as well identifying theoretical gaps present around the core category.

3.6.5.4 Theoretical Coding

Theoretical coding is the final stage of the GT process as it attempts to integrate larger concepts and variables around the core category, dubbed the Basic Social Process (BSP) by Glaser (1978). This BSP is the main concern of the participants that is being resolved in the phenomenon under study.

Glaser (1978, 1992) utilises coding families for which integration of variables can be achieved. He stresses that coding families are employed only according to the extent to which these are grounded in the data and how useful these are in the context of study. Corbin & Strauss (1990) recommend an ‘axial coding paradigm’ and a ‘conditional matrix’ prior to theoretical coding, a prescription that has received criticisms from both Glaser (1992) and Charmaz (2014) for the forcing nature of a single coding paradigm. Charmaz (2014), on the other hand, takes a neutral stance to coding families in general, suggesting that coding families can either “…help you specify possible relationships between categories..” or “impose a framework on your analysis”.

Once a theory has been developed, the literature is reviewed as a source of further data to incorporate into the theory and also connect the theory to the wider body of theoretical literature (Glaser, 1992). Critically, the extant literature may be treated as abstracted data, where the paradigms of the researchers and their approaches are also treated as data, not only the findings that they put forward.

3.6.5.5 GT for Secondary Data Analysis

The aim of GT is not to only generate theoretical concepts in relation to data, but to integrate into the wider literature which surrounds the study. This may also include the use of secondary data in order to further develop the GT. Importantly, such data is not necessarily treated as internally different to the literature. Unlike primary data, where the investigator may have significant control over the data collection process, both literature and secondary data are only accessible through another's interpretative lens. Can such data be used for a GT analysis?

The founders of GT would appear to respond in the affirmative (Glaser, 1998; Glaser and Strauss 1967). That being said, secondary data analysis for GT is not often employed in practice according to Birks and Mills (2015) who highlight that the "philosophical perspective and aims of the original researcher will have influenced the nature of data they have gathered and how they approached the processes of data generation and collection" (p. 158). They go on to highlight the main issue around secondary data there are some requirements from secondary data, specifically around data quality. If not raw data, or excerpts of raw data, it is important that secondary data is sufficiently rich and descriptive, even if this is imbued with the researchers' interpretations. Glaser (1992) would argue that even the researchers' interpretative framing and presentation of the data can be considered data.

Another issue is the limited influence a researcher has on theoretical sampling when exclusively using secondary data. The goal of theoretical sampling is unlikely to be achieved when relying on secondary data solely (Birks & Mills, 2015; Whiteside et al., 2012).

Reflexive Commentary

In this research, I employ the use of secondary data for further development of the grounded theory (see Chapter 6), and my justification for this is based on two premises.

First and foremost, these secondary data were only analysed once I believed that the primary data collection and associated analysis appeared to be relatively saturated. In fact, since the study focused on a single site for exploration, albeit over different deliveries and participants, the resulting analysis could be argued to be bounded too closely to the specifics of the context of primary data collection. From this perspective, inclusion of data generated from different contexts adds to the validation process of the presented grounded theory.

Second, both of the studies employed (Goncher, 2012; Morgan, 2017) were rich in terms of data quality and contextual overlap with sufficient variability; both involved examples of qualitative exploration of undergraduate engineering design projects but varied in terms of duration, complexity and engineering sub-discipline. Goncher (2012) included transcripts of students' interactions in naturalistic design environments. Morgan (2017), on the other hand, employed an ethnographic approach to presentation of observations of various design meetings. Here, I found the interpretive lens employed by Morgan to be helpful in conveying the atmosphere and "feeling" of design meetings, with selective excerpts from participants, which can often be lost from verbal-only transcripts of interactions. I do not view such interpretations as unwelcome subjectivity, rather I find these to be valuable inclusions, and data itself, as it positions Morgan's perspective with the data which offers transparency into the interpretations.

I do not view all secondary data as inherently compatible with my approach to GT, but I believe the inclusion of these two works, specifically, have benefitted the analysis.

3.6.5.6 Memo-writing

Memo-writing in grounded theory is a tool used in the GT method to assist the researcher in theory development. All variants of the GT method emphasise the importance of memo-writing as a multi-purpose analytic tool. Memos function to keep track of methodological decisions and provide an audit trail; develop categories by comparison of data, incidents and concepts (Charmaz, 2014); identify areas for potential theoretical sampling; and monitor changes in analytical directions (Wuetherick, 2010). Glaser (1978) suggests that the primary purpose of memo writing is to complement the method and address each stage of the analytical coding process. For open coding, memo-writing has the function of raising data to a conceptual level; for selective coding it brings in connections between concepts to assist in identifying the core category; and, for theoretical coding, it functions as a tool to integrate the categories into a theory.

3.7 Revisiting Quality in Qualitative EER

As has been highlighted throughout the discussion, the validation criteria outlined by Walther et al. (2013) are well-addressed through the techniques employed in the grounded theory approach taken in this study. Table 3.2 summarises the techniques employed and the criteria addressed in the process-orientated validation model presented at the start of the chapter. It is evident that many features of GT qualitative research align well with Walther et al.'s (2013) validation criteria.

Table 3.2 Techniques employed which address Walther et al.'s (2013, 2017) validation criteria

Criteria	**Techniques Employed for Validation**
Theoretical Validation	Emergent approach to research design; inductive-abductive approach to analysis
Procedural Validation	Triangulation (analyst and sources) and the constant comparative method
Communicative Validation	constant comparative method; iterative data collection/analysis; using literature to connect theory
Pragmatic Validation	prolonged exposure to practice; explanatory power of emergent theory
Ethical Validation	Reflexivity; memo-writing; relevance of theory to lived experience
Process Reliability	Transcript checks; training in research procedure; cross-checking

3.8 The Reflexive Journey from Classic to Constructivist GT

The transitional experience of undergraduate students has been thoroughly explored in the literature, primarily through quantitative studies concerning self-perceptions of skills, involving the assignment of importance to at times vague and abstract skills. Furthermore, there is no consensus on how these skills are *understood* by participants of such surveys. Although some qualitative research exists, the purpose of this study was to develop research outputs that would be of use to practitioners, primarily students, staff members, course co-ordinators, and graduates. It is hoped that the understandings obtained from this study may be used to inform interventions for action research too.

Reflexive Commentary

A research method that would allow for variability and, indeed, thrive with such conditions was necessary. Retrospectively, this became especially important as the CE design project in the three years of study was delivered with slight variations in delivery. I wanted to focus on capturing experience with a view to elucidate understanding of the phenomena that was occurring, to speak to practitioners and offer some utility in the phenomena that they find themselves in.

I was attracted to the grounded theory method as it did not entail pre-emptively deciding to subject the study to a deductively contrived theoretical framework. Initially, I inclined towards the literature centred around communication, however, from my own experiences with the design project, I found that the theory spoke little to my concerns as a student during design itself. It is for this reason I approached the literature around GT.

Throughout the discussion presented it can be observed that reference is primarily made to the Classic and Constructionist approaches to GT. I include here a brief discussion of my introduction to GT and how my leanings towards constructionist GT developed.

Initially, after seeking out inductive approaches to social inquiry, I came across the work of Glaser & Strauss (1967) and found it spoke to me well. After some research I came across *Basics of Qualitative Research* by Corbin & Strauss (1990), which I found to be lacking in practical advice to a novice qualitative researcher such as myself and I found the *language* of the work to be a particular obstacle. It was at this point I explored other forms of GT and was immediately drawn to the work of Glaser. Classic GT spoke to me, an engineering graduate trained in the post-positivist paradigm. Variables and data were put forth in almost mathematical fashion, representative of the quantitative training of Glaser. This familiarity in language brought me to follow classic GT. I found GT, as it was put forth by Glaser, to be comprehensible and coherent.

I became conscious of the problematic philosophical underpinnings of the Classic GT approach through the study of research philosophy. Opposition of researcher preconceptions, bias and 'forcing' within the Classic GT have become the distinguishing characteristics of Classic GT, yet Glaser does not fully address the epistemological conundrum at the heart of his approach. I have come to appreciate that Charmaz (2014) has captured the essence of Classic GT but with a strong awareness of the interpretive nature of GT. In my study, I have found generally close alignment with the practical aspects of GT in both the Classic and Constructionist variants.

Where constructionist GT excels is the emphasis on researcher reflexivity in the approach, and it is my belief, owing to this quality, it captures a more comprehensive study of social phenomena. For this reason, I align with the philosophical underpinnings of the Constructionist approach and take practical aspects from the classic approach.

Chapter 4. Research Setting and Methods

4.1 Introduction

This chapter describes the qualitative research methods employed within this study, with particular emphasis on the emergent quality of the research design. The chapter begins with a detailed account of the research setting. Following an overview of the involved research participants, the leading ethical considerations and implications are then described. The main data collection methods are detailed with a reflexive discussion of the contextual limitations and responsiveness of the research methods employed, presented in similar fashion as the preceding chapter. The core analytic techniques and methods from constructionist grounded theory (GT) are explained with rich examples from the study. The chapter closes with a reflexive statement, to frame the position and views that influenced the research throughout.

4.2 Research Setting

4.2.1 Chemical & Process Engineering at the University of Strathclyde

Originally founded in 1796, the University of Strathclyde (UoS) was established for the education of practical disciplines, hence its motto "The Place of Useful Learning". Engineering, vocational by definition, has been at the heart of the university with just under six thousand students enrolled in Autumn 2017. The first Chemical Engineering syllabus at UoS ran in 1870. The Chemical and Process Engineering (CPE) department has been an official part of the university since it gained its Royal Charter in 1964. CPE at UoS has grown significantly over the last decade with an undergraduate intake that has increased significantly, more than doubling from 56 students in 2004 to 115 in 2015, following the national trend (see Figure 4.1).

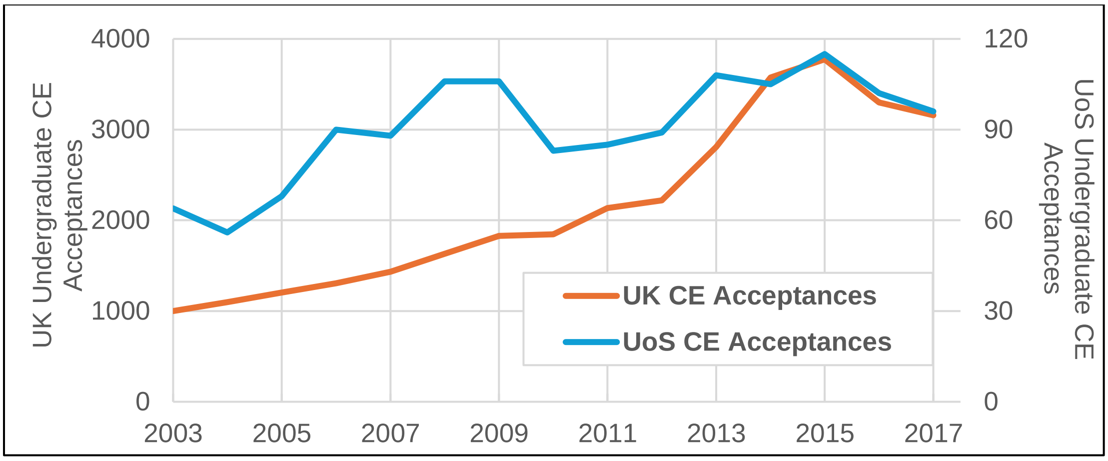

Figure 4.1 UK and UoS's Chemical Engineering Undergraduate Intake (2003 – 2017)

The rapid growth in the chemical and process engineering department places different demands on programmes, educators and students. As cohorts have grown the department has been proactive in exploring different approaches to teaching and learning to cope, working collaboratively to manage the student to teaching ratio.

4.2.1.1 Undergraduate Programmes at the University of Strathclyde

As the capstone project in the chemical engineering programme involved students on varying programmes, a brief description of students' programmes is provided for contextual transparency.

Table 4.1 Summary of Sample Modules Undertaken and Group Work Components

Year	Course	Title	Group Work
1	CH106	**Chemistry: Principles & Practice 1**	No
	MM111	**Mathematics 1B**	Yes
	CP101	**Basic Principles in Chemical Engineering**	Yes
	CP102	**Fundamentals, Techniques And Tools**	Yes
	Misc	Elective Classes	Misc
	MM112	Mathematics 2B	Yes
2	MM211	**Mathematics 3B**	Yes
	CP204	**Fluid Flow and Heat Transfer**	No
	CP207	**Process Analysis and Statistics**	Yes
	CP206	Chemical Engineering Practice 1	Yes
	CP205	Safety and Project Management (**ACCE take Safety**)	Yes
	CP203	Thermodynamics and Chemical Principles	Yes
3	CP302	**Mass Transfer and Separation Processes**	No
	CP304	Reactors and Biochemical Engineering (**ACCE take Reactors**)	Yes
	CP303	Materials Processing & Application	No
	CP305	Ethics, Sustainability & Economics	Yes
	CP306	**Chemical Engineering Design & Advanced IT**	Yes
	CP307	Chemical Engineering Practice 2 (**ACCE take half of CP307**)	Yes
4	CP404	Particle Technology and Multiphase Systems	Yes
	CP405	**Process Control and Environmental Technology**	Yes
	CP409	Advanced Separations and Problem Solving	Yes
	CP407	**Chemical Engineering Design (60 Credits)**	Yes

N.B. Modules are 20-credits (10 ECTS), unless stated otherwise. ACCE take modules in bold.

Students participate from the following programmes (in order of greatest student proportion):

- (Integrated) Masters in Chemical engineering (MEng)
- Bachelors in Chemical Engineering (BEng)
- (Integrated) Masters in Applied Chemistry and Chemical Engineering (ACCE) (MSci)
- Exchange Students

Although the programme changes year-by-year, a representative list of modules in the programme are provided in Table 4.1. Among the notable features in the programme is that majority of the modules comprising the degree entail a significant degree of group work. Included in the category of group work are activities such as regular tutorials (where groups are explicitly defined), assignments, laboratory work, projects and presentations.

Exchange students typically participate in a year of the programme or for BEng programme in its entirety. ACCE students take a selection of modules with both the CPE department, as highlighted by the bold items in Table 4.1, and the chemistry department. Included in these separate modules are physical, organic, and inorganic chemistry as well as chemistry laboratory.

The CPE department also delivers a distance learning programme which includes a capstone project; however, this group was excluded from the scope of this study. In this study, majority of students were enrolled on the MEng or BEng programmes which also entailed the same course structure and modules up to and including the design project (see Table 4.1). MEng and MSc students anticipate an additional year of their respective programmes, whereas the capstone project is the final course activity for BEng students.

4.2.2 CP407: Chemical Engineering Design (CE Design)

The final design module in the CE programme at Strathclyde, is titled "CP407 Chemical Engineering Design" (henceforth referred to as *CE Design)*, and is a 60-credit module which exclusively occupies the final semester of the 4th year Meng/BEng programmes.

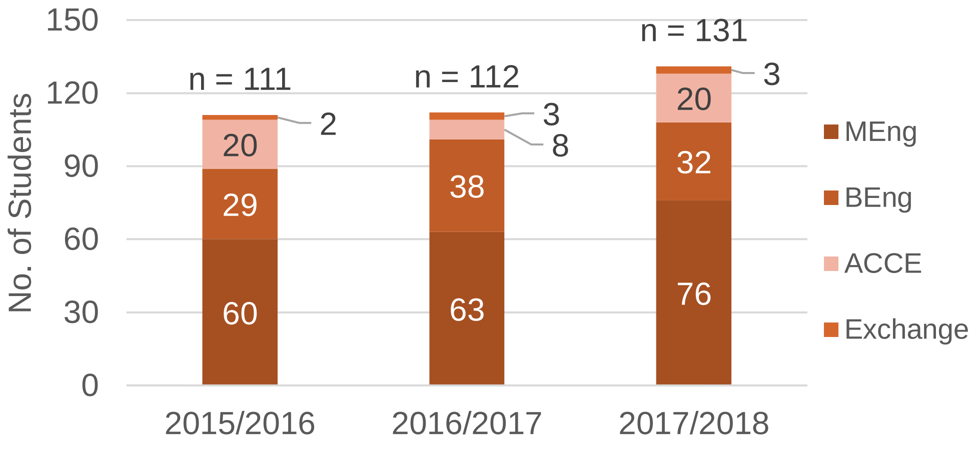

Figure 4.2 Annual Design Student Participation by Programme for Studies Years

Figure 4.2 shows the breakdown of students participating in CE design for each year under consideration in the study. Table 4.2 summarises the format that design took during the years of study. Characteristic to design is the allocation of a small number of student groups (typically 2 or 3) to an academic member of staff who acts as a 'supervisor' and evaluates accordingly. Design is typically arranged as phases: the 2016/2017 iterations involved three phases and for the 2018 iteration the final two phases were combined. These changes capture the responsive pedagogic redesign of design as the module registrar received feedback from students' and staff's experience of the design project throughout the years of the study.

Table 4.2 Design Format & Assessment for Studied Years (2017 shown in square brackets)

Year of Study	**2016 & [2017]**			**2018**	
Number of Phases	3			2	
Brief Title	2016: *Production of Anhydrous Ethanol from Sugar Beet* [2017: *Production of Ibuprofen*]			*Production of Anhydrous Ethanol from Sugar Beet*	
Phases	Feasibility /scoping	Detailed design	Economics and	Feasibility /scoping	Detailed Design, economics, sustainability
Duration (weeks)	4 [4]	4 [5]	3 [2]	4	7
Assessment	Group	Individual	Group	Group	Individual + Group HAZOP
Grade (%)	26.7%	40%	33.3%	30%	70%
Assessable Outputs	Report Presentation Peer-assessment*	Report	Report	Report Presentation	Report

**N.B. Peer-assessment was in place for 2016 only*

4.2.2.1 The Design Brief

The design brief provided to staff and students contains all relevant information related to design. The brief opens with direct reference to, and explicitly reports, the learning outcomes mentioned in IChemE's accreditation guide. The brief then includes contextual information to establish the relevance and importance of the design problem statement, followed by articulation of the design 'task'. The design 'task' involves the design of a preliminary chemical process plant to fulfil the design criteria and to evaluate the sustainability of the proposed design. The following is an excerpt from both the 2016 and 2018 design brief documentation:

> Your design group has the task of producing a preliminary design of a process to convert raw sugar beet to anhydrous ethanol. The finished product must meet the EU specification for de-natured ethanol EN 15376. The design output is to be either 10,000 m^3, 100,000 m^3 or 1,000,000 m^3 of anhydrous fuel grade ethanol per year. These volumes can be produced only in specific parts of the world due to various economic and environmental factors governing supplies, regulation, transport, infrastructure, etc. The plan is to produce these in different countries and different volumes in different locations shown below. The plant may be designed to operate all year round, but not necessarily at uniform output. Different groups are expected to develop different designs as per the requirements specified. (2016 Design Brief)

Following some suggestions for students to consider, the design brief formulates the phased approach to design. Phase 1 involved conducting a review of literature with student groups producing a feasibility study and delivering an oral presentation for the proposed design and initial plant overview, recommending changes to the brief if necessary. Phase 2 involved individual detailed technical design of equipment for the proposed plant, including associated costing and safety considerations. Phase 3 involved an assessment of the economics and safety aspects of the plant, for which students produced a group report and participated in an isolated hazard and operability (HAZOP) exercise delivered and assessed by representatives from an industrial organisation. In 2018, much of phase 3 was incorporated into the individually assessed phase 2, with the HAZOP activity being made into a distinct activity run towards the end of the second phase.

Key “deliverables” along with associated milestones, mark breakdown and relevant formatting criteria for each phase are also articulated in the design brief documentation. For each year, the details for each of these aspects changed somewhat. Although some of these criteria seemed unimportant, their significance was highlighted by multiple participants during interviews and observations. For example, the 2016 design brief stipulated a maximum of 3000 words for individual phase 2 reports, which was changed to 12 individual pages in 2017, and again altered to 100 pages for the whole group submission in 2018. A complete brief for 2017 is provided in Appendix A1.

4.2.2.2 Design Participants

Table 4.3 provides details of the number of staff and students and group arrangements for each of the studied years, for which student groups were randomly assigned. Student groups were supervised by two supervisors whose responsibilities involved participating in supervisory meetings and evaluating design deliverables. For both 2016 and 2017 iterations of design, one supervisor was responsible for phase 1 (scoping) and phase 3 (economics and sustainability analysis), while another supervisor was assigned for phase 2 (detailed design). In 2018, students were supervised by a pair of supervisors throughout design. The design brief stated that "the supervisor is an advisor (and not a tutor)."

Table 4.3 Breakdown of number of students and Staff for Years of Study

Year	2016	2017	2018
Number of Students	111	113	131
Number of Staff	15	17	20
Staff P1/3	6	7	20
Staff P2	9	10	20
No. of 7 Member Groups	15		17
No. of 6 Member Groups	1	18	2
No. of 5 Member Groups		1	

Although the design involved little scheduled contact between students and staff, weekly hour-long supervisory meetings took place throughout the design process in departmental meeting rooms. The purpose of these mandatory meetings was primarily "to update [the supervisor] of the progress of the Project." (2016 Design Brief). However, the design brief also informs students that "the purpose of these meetings is to raise project related queries with your supervisor, which you cannot answer as a group. The meetings are not a forum to resolve detailed technical or engineering issues; these issues should be dealt with separately amongst the group members."

4.2.2.3 The Design Setting

Supervisory meetings took place in booked meetings rooms located within the department of Chemical and Process Engineering at scheduled weekly times.

Students were not obliged to meet with group members, although recommendations were made for students to meet regularly for group meetings. Students, whose work usually involved computer access, were not provided with formal spaces to complete design. In such circumstances, students would often work in various areas including available computer laboratories in the department (see Figure 4.3) and around the campus; the university library; and at home.

Students were provided with cloud storage facilities to share files and collaborate, however often students would make use of other services that they preferred. Similarly, although provided with university email accounts, students would often arrange their own processes to communicate with group members through preferred instant messaging services.

Figure 4.3 JW410 Computing Laboratory

4.3 Research Participants

In both 2016 and 2017, deliveries of design to six groups were observed as they progressed through the design project, details of which are provided in Table 4.4. A total of 79 hours of observations were made, of formal design interactions in the form of both supervisory meetings (67 instances) and the presentation component (12 instances). Groups that were observed were selected to maximise unique combinations of supervisors and based on the researcher's schedule and availability.

Table 4.4 Number of Instances of Formal Supervisory Design Meetings Observed

Year	**2016**	**2017**
Phase 1	12	6
Phase 1 Presentations	6	6
Phase 2	16	17
Phase 3	7	9
Total	41	38

As part of the interviewing process, a total of 24 interviews were conducted with 21 unique interview participants, the details of which are presented in Table 4.5. Note that all names presented are pseudonyms, used throughout the study to protect the identities of the participants.

Table 4.5 Interview participants details (all names are pseudonyms)

Interview ID	Pseudonym	Programme	Design Year	Interview Details
1	Sarah French	BEng	2016	Post-design interview (6 months)
2	Billy Reynolds	MEng	2016	Post-design interview (6 months)
3	Spencer Jennings	MEng	2016	Post-design interview (7 months)
4	Omar Ahmed	MEng	2017	Pre-design interview (2 weeks)
5	Will Ross	MEng	2017	Pre-design interview (2 weeks)
6	-	MEng	2016	No design project discussion
7	Ellis Donaldson	MEng	2017	In-design interview (phase 1)
8	Cain Bruce	MEng	2017	In-design interview (phase 1)
9	Frank Hill	MEng	2017	In-design interview (phase 2)
10	Will Ross	MEng	2017	Follow up in-design interview (phase 2)
11	Cain Bruce	MEng	2017	Follow up in-design interview (phase 2)
12	Ewan Murray	MEng	2017	In-design interview (phase 2)
13	Cameron Hooper	MEng	2017	In-design interview (phase 2)
14	Iona Mitchell	MEng	2017	In-design interview (phase 3)
15	Emelia Emese	ACCE	2017	In-design interview (phase 3)
16	Ellis Donaldson	MEng	2017	In-design interview (phase 3)
17	-	-	2017	Audio recording issues.
18	-	-	2017	Did not meet inclusion criteria
19	Will Ross	MEng	2017	Follow up in-design interview
20	Natasha Douglas	MEng	2017	Post-design interview (2 weeks)
21	Phillip Easter	MEng	2017	Post-design interview (3 weeks)
22	Laura Dawson	MEng	2018	Post-design interview (1 year)
23	Sophie Duncan	MEng	2018	Post-design interview (1 year)
24	Aman Chowdhury	MEng	2018	Post-design interview (1 year)

From these interviews, 21 were deemed usable, with 16 unique interview participants, and corresponding transcripts were generated. 2017 iteration of design. Although no specific demographic information was collected, interview participants were comprised of 6 women and 10 men – there was a slight overrepresentation of women based on the trends of the CE cohort course in general (20 – 30% female). One interviewee participated in two follow-up interviews and another participated in a single follow up interview.

An overview of the research methods and related activities are provided in Figure 4.4 and are explained in the subsequent sections in more detail.

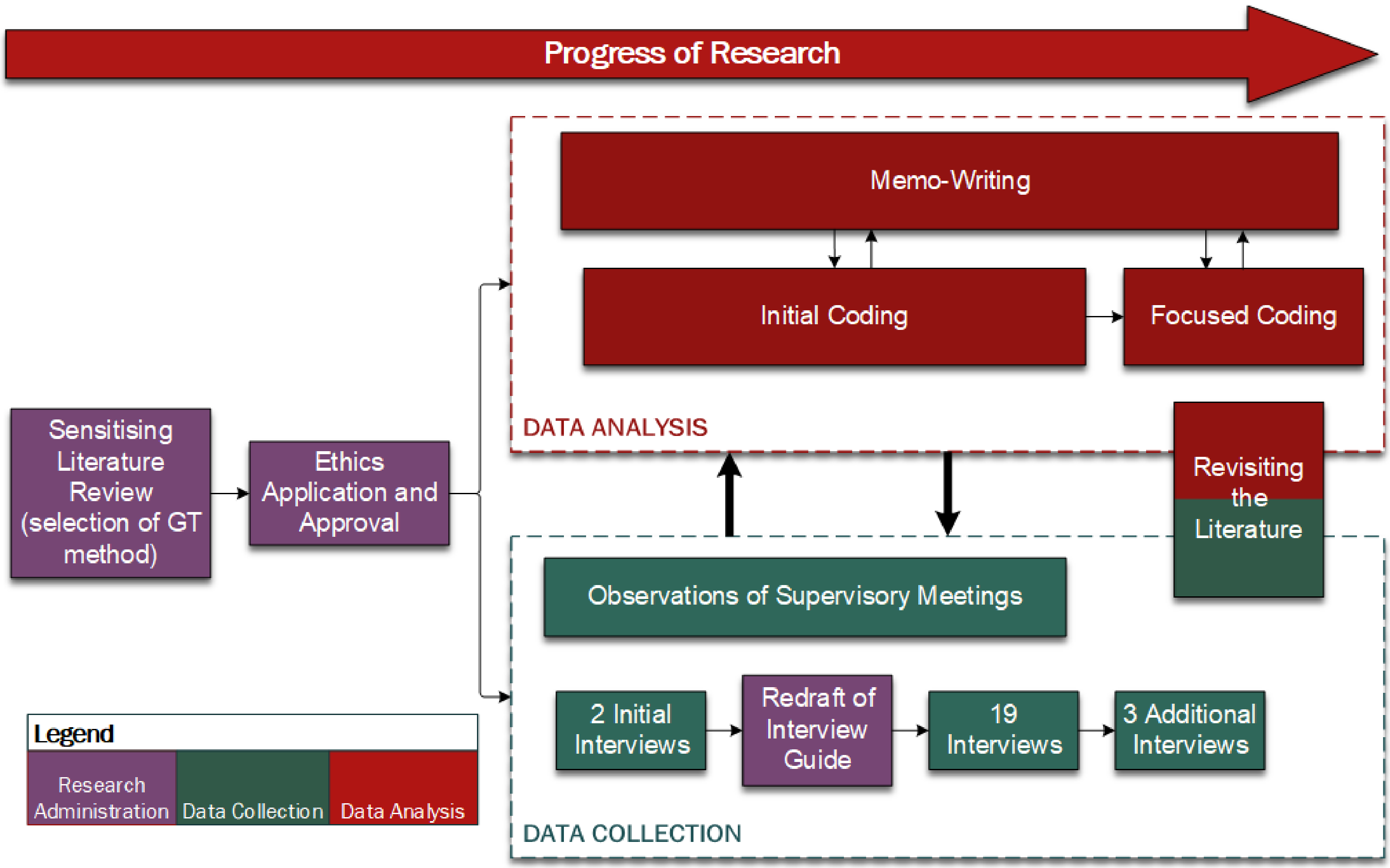

Figure 4.4 Overview of Research Process

4.4 Ethical Considerations

All research involving human participants requires ethics approval from the University of Strathclyde's ethics committee. This study obtained ethical approval via the chemical and process engineering departmental ethics committee on behalf of the university ethics committee. An example information sheet, and consent form can be found in Appendix A2.

Informed consent was an ethical issue that needed to be addressed for the observations and interviews. For observations, in advance of the initial supervisory group meeting, staff were approached in-person, and the details of the study explained. After verbal agreement with selected design supervisors, an email was sent to the supervisor, which they then forwarded on to their student group. The email contained information about the study and how to get in touch with the primary researcher should they not wish to participate. At the start of the initial meeting, the purpose of the study was re-articulated to students, and participant information sheets and consent forms were provided for reference and signing. It was emphatically stressed that participation was completely voluntary, and should students choose to not participate, this would be immediately respected, and students could communicate this either in-person, via email or an online form. There was only one response where a student requested to not participate in the study and hence supervisory meetings for that group were not observed.

For interviews, the students were recruited via an advertisement email distributed by administrative staff, which asked students to contact the primary researcher if they wished to participate in an interview. For participation in interviews, students were reimbursed by a £10 voucher to an online retailer.

All digital data collected – such as audio recordings, associated transcripts, and transcript keys – were stored on the password-protected, personal, encrypted cloud storage and server provided by University of Strathclyde (UoS). Completed consent forms and notebooks containing observational field notes were stored securely under lock and key, with only the primary researcher having access to these documents.

As some of the participants were undertaking the design project at the time at which the interviews were conducted, confidentiality was an ethical issue addressed within this study. To maintain participant confidentiality, interview participants were provided with the option to conduct the interview off-campus at nearby cafés. This was offered to students in case there were concerns related to confidentiality if the interview took place in a departmental meeting room. All transcripts were pseudo-anonymised, which involved assigning pseudonyms to all identifiable individuals, peers and academic staff as well as the alteration of any reference that would otherwise render the participant identifiable.

Initially, consent was sought for only the primary researcher to have listening rights to the audio recordings, to maintain confidentiality. This was not extended to my supervisors, as they were also participants of the design project in their capacity as supervisors. However, in the interest of research rigour, it was deemed appropriate to seek retrospective consent from participants for the research team to review audio recordings to perform transcript checks, for which all accepted.

As this additional consent was being sought, digital copies of the relevant pseudo-anonymised transcripts were attached in communication with participants for member checks to be conducted.

Reflexive Commentary

This retrospective implementation of quality checks into the research process is an indication of my own developing understanding of quality in qualitative research. The experience of this study has provided me with greater appreciation for thorough research design. While I acknowledge that the limitations in delaying such checks, especially member checks, may have an impact on their reliability, it does not preclude their worth to the overall research quality. This responsive and emergent approach to research design helped to ensure the ethical and communicative validity of the research (Walther et al., 2013).

4.5 Data Collection

4.5.1 Participant Selection

The main inclusion criteria for interview were that students had to be either planning to participate, undertaking, or had participated in CE design delivered by the University of Strathclyde's Chemical and Process Engineering Department. The dominant sampling protocol was convenience sampling, as students were recruited via an email call for interview participants. However, the timings of interviews relative to participants' design involvement were varied to capture the process of design at different stages. This promoted investigation of the lived experience quasi-longitudinally and aimed to capture the evolving participant interpretations of design. The GT notion of theoretical sampling is discussed later.

4.5.2 Journey From Focus Groups to Semi-Structured Interviews

Initially, focus groups were considered as the main means of primary data collection. In addition to this, it was envisioned to conduct asynchronous focus groups through online communication and social media platforms, as these offered a number of anticipated benefits, including a larger pool of participants (including off-campus masters students and recent alumni); efficient means of data collection as no transcription would be required; and sustained duration of discussion to allow for reflection and conversation (Edmunds, 1999). Upon critical review of this data collection method it was deemed that the drawbacks, particularly those involving data security; accessibility; and lack of timeliness of responses (Rezabek, 2000), outweighed the potential benefits.

After further consideration, focus groups were rejected in favour of individual interviews. Influencing this decision was awareness of the methodological, pragmatic and contextual limitations of focus groups with respect to this study. From a methodological perspective it was deemed that focus groups, while offering an efficient means of increasing the number of participants involved in the study, did not fit well with the grounded theory assertion of 'constant comparison'. Charmaz & Belgrave (2012) critiqued the exclusive use of focus groups for data collection, as such studies "often relegate grounded theory methods only to data analysis" (p. 354).

Reflexive Commentary

In addition, I was aware of my limited skill in moderating focus groups as a novice researcher. Prior to this research study, I had neither experience in conducting focus groups nor individual interviews. I believe that to become better at these data collection methods, one must learn through practice, however, initial data collection may be impacted as I learned how to conduct these. It was expected that the associated impact on research progress would be greater in the case of focus groups with regards to quality of data collected owing to my lack of experience.

My own experience as an undergraduate studying design and tutor for various modules, prior to this study, led me to believe that interviews would provide more meaningful data. Among the chief concerns was that the highly socialised nature of the cohort. My justification for not proceeding with focus groups was that students were generally well-acquainted with one another, and I believed that focus groups may deter students from responding with candour – ultimately masking possible meaningful insights. This prior experience is discussed in greater detail in the reflexive statements concluding this chapter.

Another aspect of data collection that was reviewed during the early stages of research was that of recording audio. Given the initial adherence towards classic GT, Glaser & Holton's (2004) criticisms against such recording was considered. Glaser (2002) argues that recording and transcribing interviews is an unproductive research activity that often leads the researcher towards qualitative data analysis that concerns itself with "worrisome accuracy" and a descriptive, rather than theoretical, approach (Stern, 2007). Glaser's (Glaser, 1998) position is that researchers should write notes immediately after interviews and observations and that these notes help the analysis progress, as this takes place close to the data collection, resulting in analysis being grounded in data.

Again, this was ruled out for practical reasons relating to both recall and researcher inexperience. With reference to the quality framework developed by Walther et al. (2017), it can be concluded that such a decision to not record audio would be in direct contradiction to the validating constructs including procedural, communicative, pragmatic validation, as well as process-reliability. While Glaser's position remains problematic, there is value in tying prompt analysis closely to the data collection, hence notes based on memory were made promptly after data collection. Over-analysis itself was overcome by coding quickly as recommended by Charmaz (2014, p. 110).

At the initial stages of participant interviews, an unstructured form was selected, as recommended by Classic GT, with a generic list of exploratory questions as a guide, as shown in Figure 4.5.

Opening Question
So when I mention the design project, does anything come to mind? [Follow up]
Exploratory Questions
Can you tell me (more) about what working as a group was like? [Follow up]
What about the supervisory meetings, what were those like? [Follow up]
Do you feel you developed in any way as a result of your experience of the design project? [Follow up]
How did you find the ways you were assessed?" [Follow up]
Did you learn anything? [Follow up – about self, academic skills etc.]

Figure 4.5 Initial Unstructured Interview "Guide" Used for Interviews 1 and 2

Reflexive Commentary

Immediately after conducting the first interview, it was evident that this style of interview did not suit my preferences as a researcher. There were clear deficiencies in my interview skills: I approached the interaction erratically and would not provide the interviewee with time to reflect on questions, interpreting silence as confusion about what was being asked. Following this first interview, I developed an intensive, semi-structured interview guide (Charmaz, 2014), an excerpt of which is presented in Figure 4.6. The full interview guide is provided in Appendix A3. As well as being more methodologically rigorous, the interview guide had a marked effect on my self-confidence in interviewing and active listening. I was able to respond well to what participants shared; follow-up on points raised by participants in a natural manner; and most importantly provide participants time for reflection and thought, prior to answering a question.

INTERMEDIATE QUESTIONS

- *Had you had any experiences of project work prior to the Group Design Project (GDP)?*
  - *What were these like and how do they compare?*
- *Before actually starting the GDP, did you have any ideas or thoughts of what it was going to be like?*
  - *Do you recall how you felt about it?*
- *Thinking back to the induction for the GDP in Barony Hall, can you tell me your thoughts and feelings as you learned what the GDP was going to involve?*

Figure 4.6 Semi-Structured Detailed Interview Guide

4.5.3 Observations of Supervisory Meetings

Supervisory meetings were observed, as these were formal sites in which interactions took place, both between students and with academic staff. Supervisory meetings were deemed valuable to observe, as these provided insight on how students interpreted the function of supervisory meetings, the role of supervisors, and the wider design experience.

Over the course of the study, selected groups from the 2016 and 2017 iterations of design were observed. For each of these years, six groups with different supervisors were selected and consent obtained from all participants for the researcher to record audio and make observational notes. A total of 67 supervisory meetings were observed, with each being audio recorded and observational field notes made. In addition to this, the assessed presentation for each group was observed and audio recorded. In total, approximately 56 hours of observations were conducted through the course of the study.

Audio recordings generated were generally not transcribed but observational notes included descriptive notes, and analytical notes were generally made in-situ. Initially, there was less focus on analysis and more attention made to description and broad reflections. As the observations progressed, these notes included greater analytical emphasis by aligning more closely to Charmaz's approach to initial coding, namely using gerunds to capture the processes involved in the observed phenomena. An example of field notes and observations are shown in Figure 4.7.

Brodsky (2008) suggests that fieldnotes "capture impressions and the researcher's ongoing analytic process." By nesting analytical notes and codes in the descriptive text, with clear timestamps, the reliability of the analytical notes was improved with important events being highlighted for later review in conjunction with re-listening to relevant audio recordings.

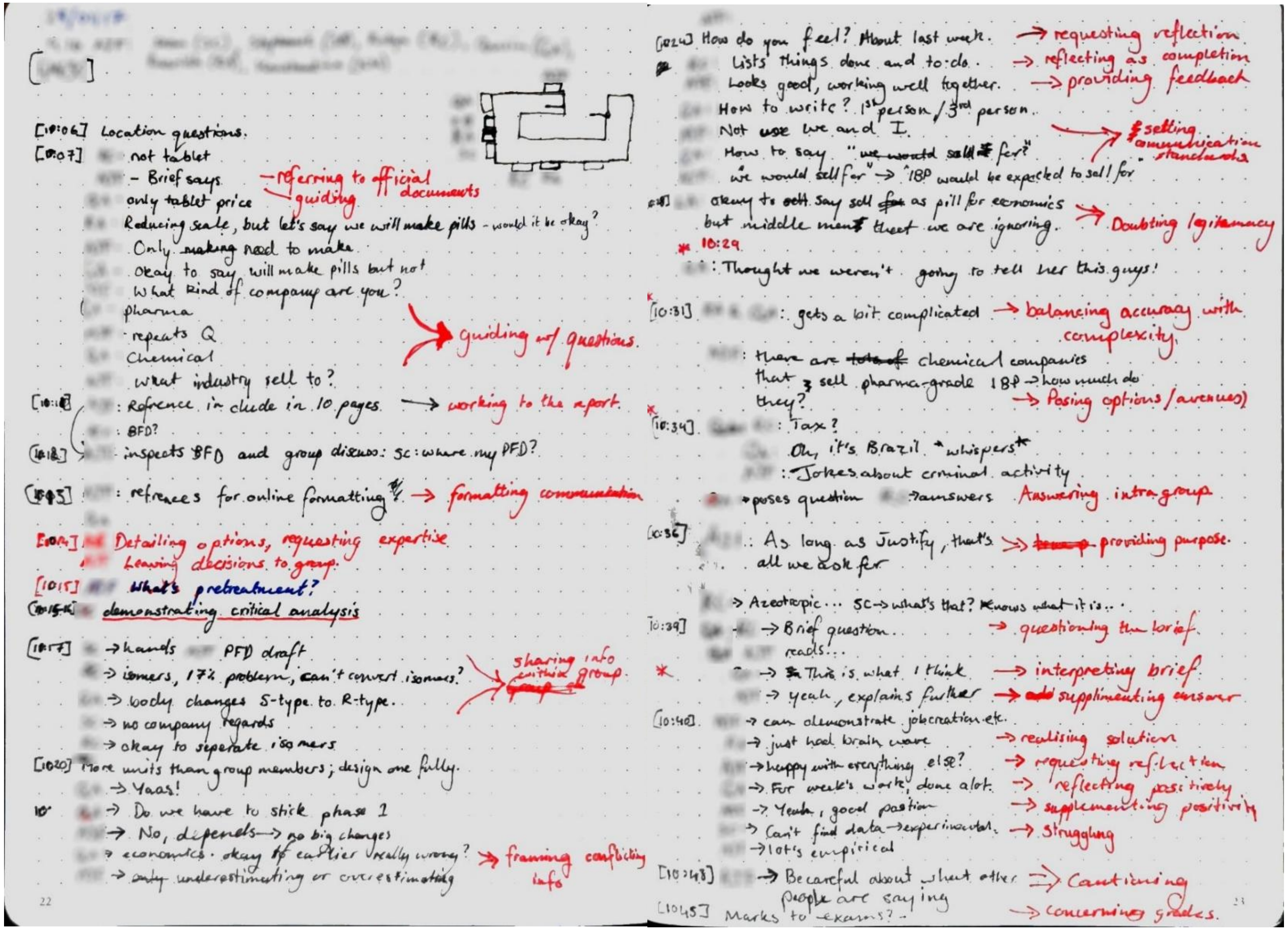

Figure 4.7 Example of observational field notes (blurred to preserve anonymity)

4.6 Data Analysis

4.6.1 Initial Coding

According to Charmaz (2014), the purpose of initial coding is to fragment the data. This fragmentation is facilitated by analysing the data at varying levels, including word-by-word, line-by-line, and incident-by-incident.

Line-by-Line Analysis	**Interview Excerpt (Cain Bruce)**
	Int: Are there any similarities or major differences between the two phases?
Feeling isolated in phase 2 (P2); Attributing isolation to assessment criteria; Being graded as an individual; Adapting to individual design; Working in close proximity (P1); Facilitating ease for communication (P1); Facilitating Feedback Working in the P1 "office"; Experiencing relative isolation; Losing informal social interactions; Forming the dynamic-autonomous group; Filling the void; Losing a support group; Losing connection; losing social cohesion of group; Reviewing early design decisions; Changing normative interactions; Adjusting to a new norm; Becoming territorial; Shifting priority from group to individual;	CB: Between the phases themselves… I mean, the isolation of phase 2 is a big aspect because it is individually graded. There is a small contribution from the group, but you do your section on your own, so this is a very different day-to-day lifestyle. Lastly, we would… We wouldn't have a proper meeting every day, but we would be in the same lab every day. Like, our group decided to do that because it was always easier to just ask the person behind you, than send a message and hope that they see it. So, it's kind of lost that, I guess, how it would feel to work in an office every day… Like, "how was your morning?" And just work for a day and get lunch together and stuff like that… It's more lonely… I'm in a room on my own eating lunch away. Sometimes I'll meet people who are from different groups who are doing something similar, we'll have lunch and stuff together and talk about the ability to… It's a different dynamic, absolutely. I certainly feel less inclined to ask my group for help on Facebook and stuff, because they have their own problems. And I asked them about my XS thing today because I was just not sure that the decision, we had made… I was like "sorry guys, but I just can't…" I think the fact that I felt the need to say sorry at the start of that message is just quite enlightening. We are a team still but… It's kind of… People are quite protective of their own thing. Which I'm trying my best not to be because what happened at this meeting…

Figure 4.8 Excerpt of Interview with Cain Bruce using Line-by-Line Analysis

Figure 4.8 elucidates the process of the initial coding and it can be observed that this facilitates a strong connection to that data, while the researcher constructs analytic interpretations. The GT perspective of coding is to avoid typifying individuals and instead focus on action (Charmaz, 2014, p. 116-117). By focusing on action, it is possible to capture the dynamic nature of the social process and the variation of the observed phenomena. This is further enabled using gerunds, which emphasise action and process, in the coding procedure. This contrasts with thematic approaches to coding, which can become easily decontextualised from the data.

The process of fragmenting the data generates codes allowing for constant comparison which, in turn, assists in the iterative evaluation of the appropriateness of codes and development of codes. The process of constant comparison runs through the entire GT endeavour and is diagrammatically represented by Figure 4.9.

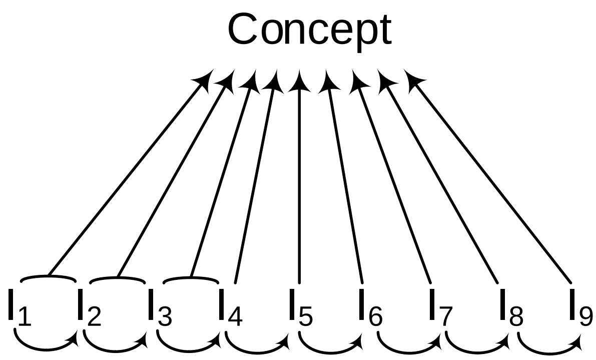

Figure 4.9 The Concept-Indicator Model, Adapted from (Glaser, 1998, p. 62)

By comparing indicators with other indicators, whether these are words, lines or incidents, concepts are specified. The conceptual codes are then further refined by comparing these with additional indicators (Glaser, 1998, p. 62) ensuring that these codes capture the variability in the data.

A special type of code that warrants additional discussion are in-vivo codes. These codes are those distinctive words, terms and phrases employed by participants themselves and are analytically incorporated into the study to "preserve participants' meanings of their views and actions in the coding itself" (Charmaz, 2014, p. 134). An example of such an in-vivo code emerging from this study is the code of ‘snaking each other’, observed in Figure 4.10.

> “There were lots of… People were kind of **snaking each other** like, “oh, you’ve done it that way. That’s a good way to do it.” And then you’d be like, “if I’ve really done it the right way and there lots of people getting better ideas.” Then you never knew if you’d done it the right way.” – *Laura Dawson*

Figure 4.10 An Example of the In-vivo Code "Snaking Each Other"

"Snaking" describes the act of misleading one's peers for the purpose of gaining a competitive advantage over them. The term 'snaking' in this example is a richer term than 'misleading', for example, as it captures meanings, experiences, actions and concerns of the participants (Charmaz, 2014).

Sensitizing concepts from symbolic interactionism, the theoretical perspective underpinning this research, informed the coding of data. These concepts, such as action, process, agency, identity, and self, assisted in drawing out analytic interpretations of the data, although care was taken that such concepts were not forced on to the data.

4.6.2 Memo-writing

Brodsky (2008) suggests that "reflective fieldnotes can be written whenever one muses on the process, findings, problems, patterns, and so on of the study. They capture impressions and the researcher's ongoing analytic process." While this perspective on fieldnotes aligns with the GT emphasis on memo-writing, memos offer greater utility in the research endeavour. Memos were used to maintain an audit trail for the research; capture operational developments; highlight personal reflections and biases related to the research study; and raising focused codes to conceptual categories (Charmaz, 2014). Memos took a variety of formats including audio recorded notes, digitally typed notes and handwritten notes.

> I think it may be a good idea to explore the process of 'dynamic-autonomous grouping' by following dynamic-autonomous group formation right through to its termination. For future interviews, if a dynamic-autonomous group is mentioned, **I must ask how these were formed, what happened preceding the formation, what life was like in the dynamic-autonomous group and how did the members terminate the dynamic-autonomous group**. Dynamic-autonomous groups are a really interesting phenomena and could be an interesting aspect for a paper too!

Figure 4.11 Excerpt of an Operational Memo on Dynamic-Autonomous Groups

Although emergent and responsive research design is often considered to be a benefit associated with qualitative research, this must also be captured appropriately. Operational memos, like that presented in Figure 4.11 , helped to capture one of the distinguishing characteristics of GT: the iterative relationship between data collection and analysis.

Reflective memos provided a creative space to collect my own musings and thoughts related to the study. There was no fixed structure employed and no limitations placed on the content for reflective memos. Writing prompts recommended by Charmaz (2014), such as free-writing - continuous and unrestrained writing for a set period of time - helped to elucidate any potential biases and overcome conceptual blocks. Some reflections generated from free writing, such as the example presented in Figure 4.12 (following a Coding Memo 4: Feeling Mean Withholding Work/dreading loneliness), proved to be sufficiently analytical, providing multiple interpretations, and were later incorporated into more formal coding memos.

There is a sort of hive-mind working here, students belong to this cohort, and they act in accordance with what benefits the cohort (or at least homogenises the experiences of members of the cohort). Individual effort must benefit the collective when one accepts this, again benefit of the collective can be the disadvantage of individuals. When a student is initiated into this collective, they get the benefits of access to the efforts of other's work; the open sharing of information; the agreement of some terms... they look out for others in the collective; they communicate well. All this is done, but I think on the individual level, each member of this collective is acting with bounded rationality to opt for what benefits them the most. It is 'safer' for students to conform with the collective than go against them. This is the accepted norm. This could be a reason why students keep comparing contributions centred around quality on P2 - yet they still do this in P1 too. It is to seek individual benefit by taking from the collective but this too feeds into the collective and hence individual benefit while belonging to the collective results in homogeneity.

Figure 4.12 Reflective Memo Generated Through Free-Writing Process

Categorising, clustering, and diagramming were other methods through which the data was explored and also raised to higher level conceptual categories. These memo-based approaches involved using the constant comparative method to generate quick visual representations of ‘what is going on’ in the data (see Figure 4.13). This iterative approach was employed to generate new connections between data and incidents.

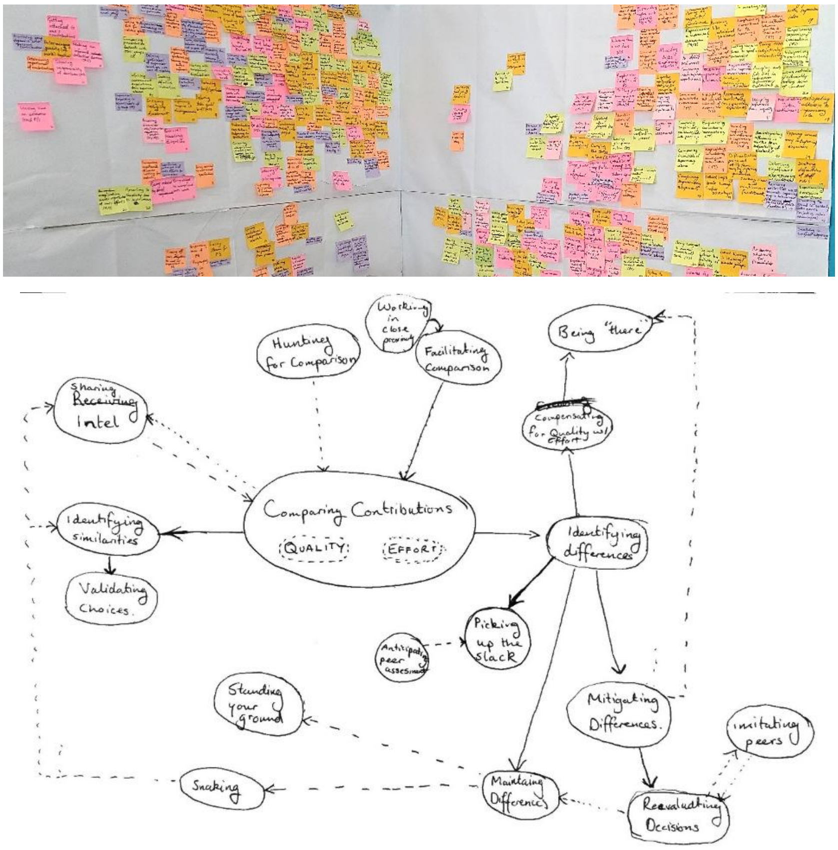

Figure 4.13 Above: Clustering generated from Codes from Line-by-Line Analysis with Post-its. Below: Diagrammatic clustering based on the central category of ‘Comparing Contributions’

In addition to this, memos were shared regularly with, and expanded on by, the research team. Occasionally the research team would engage in clustering. By engaging in a dialogue with the supervisors, new and interesting perspectives were gained and incorporated into the developing analysis. This close involvement of the supervisors in the on-going analysis, is one of the chief concerns of Walther et al.'s (2013) communicative validation construct, which advocates researchers to foster a "community of interpretation" (Apel, 1972). This proved to be a valuable and beneficial part of the research.

4.6.3 Focused Coding

Focused coding involved reviewing codes generated through initial coding and identifying those that were frequently emergent in the data and hence useful to analyse batches of data. Focused coding entailed comparison of initial codes to data; comparison of codes to codes and finally revisiting of old data with selected or focused codes to further conceptualise these.

Focused Coding	**Interview Excerpt (Sophia Duncan)**
	Interviewer: So, what, if anything, did you find challenging?
Constraining design with supervisor feedback;	SD: I found lots of things challenging [laughs]. I thought in the feedback sessions that we had with our supervisors, I thought it was quite difficult to ask nitty-gritty questions. Questions about the actual design that you were doing because sometimes you wanted their opinion to know whether to go ahead with it or not – whether what you're doing was actually correct. But they were really reluctant to give away somethings, because they are going to be marking it in the end. So, you had to use your own judgement when you are quite unsure of some stuff…
	Interviewer: So, how did you manage that?
Forming autonomous-dynamic group; Comparing design solutions Constraining design with peer feedback;	SD: That is when the other group that we kind of split into in phase 2 – when I started talking to everyone else was designing the same unit as me – that's where we would talk to each other and maybe some of us had encountered the same thing. You could see what they were doing and whether they thought it was correct. That was really helpful. Because, I understand why they didn't want to give anything away. But, you're kind of turning up to those meetings like, "what do I ask?"

Figure 4.14 Interview Excerpt with Focused Codes

In addition to this process, inspiration was taken from Glaser's (1998, pp. 74–82) 18 coding families. These coding families were incorporated as theoretical sensitizing codes to further focused coding. Prominent coding families included: the six C's (causes, contexts, contingencies, consequences, covariances and conditions), process, degree family, dimension family, type family, strategy family, interactive family, identity-self family, cutting point family, means-goal family, consensus family, and mainline family. Although used, deliberation and trial and error meant that codes were not “forced” on to the data.

4.6.4 Theoretical Sampling

Charmaz (2014) acknowledges that the practice of theoretical sampling is difficult to implement for a variety of reasons. One of the main motivations for conducting theoretical sampling is to draw out variation in the prominent categories developed through focused coding. One way in which theoretical sampling was incorporated into this study was the elicitation of comments from participants on categories presented in a contextualised manner. This explicit, even “provocative approach” (Charmaz, 2014, p. 211), generated fresh insight into the social phenomenon under study, and added to the communicative validation of the research similar to that of member checks (Walther et al. 2013). Therefore, as the research process continued, any tentative categories were developed further by eliciting comments from participants.

WR: …it was good, having the phase 1 where it is quite general, familiarise yourself with it and get to know the group. Because you really needed, or at least I really benefitted from that sort of intermediate level of applying myself in phase 1, to sort of develop relationships with Tyler and Louie in terms of what are our working relationships, which really helped me in phase 2. I can like, go into uni and work together, even though it was individual. We did still support each other a lot.

Interviewer: I guess, from other interviewees, in phase 2. There is a phenomenon where… It doesn’t entail working in a group. Some people choose to work together with other people.

WR: Oh, as in who are doing the same thing?

Interviewer: Yes.

WR: Ah, okay.

Interviewer: I’m not sure if you were aware of that?

WR: I did get the feeling… I didn’t know how many people actually did that, I know for certain things… Actually, no people would work very much in their groups towards the end. Like, people from other groups who had been working together. I didn’t do that at all, for my bit. Like, when I say the three of us were working, I mean we were all working on different tasks of the same process because we were in the same group. Yeah, it will affect my… My grade wouldn’t be as good as the ones who work together because they had more people on it. But it doesn’t bother me because I don’t need my grade to be incredible to still be… Because my past grades. Yeah, there was a lot of things going on, meaning that people got better grades than they should have.

Figure 4.15 Excerpt of Elicited Response from Participant for Theoretical Development

In the above excerpt, the student was prompted to comment on a repeatedly reported phenomenon and concept (inter-group member collaboration). The student did not mention this aspect in his experience of design and so an interpretation of these acts was elicited; his response added further properties of the concept, adding student’s progression on the programme as a conditional factor.

The above descriptions demonstrate the approach taken to conducting the research and how the methods emerged and developed through a process of testing and revision. The specific techniques and methods involved in the study have been described in detail, to offer sufficient context for the reader.

4.7 Closing Reflexivity Statement

The following is a reflexivity statement to position myself in the research. The purpose of this is to communicate clearly to the reader the background and inevitable biases held by me as a researcher. It also allows the reader to gauge how my biases have impacted the research.

Blumer's notion of 'informants'; those individuals that are knowledgeable about the area of study is of relevance to this study. All investigators, i.e. myself and my supervisors, were 'informants' to a varying extent; and I too, as is characteristic in the symbolic interactionist view, am a "role-taking" (Blumer, 1969) informant who engages in constructing emerging meanings.

My own understanding of design emerges from my experience as an undergraduate chemical engineering student who completed the Masters’ programme and completed the design project in 2013. This experience allowed for me to gain insight into design that may not be feasible from interviews and non-participatory observations on their own. Through this study it was possible to explore the parallels and dissimilarity in students’ accounts with that of my own. Specific and striking events that formed my experience of design were also used as conceptual data for constant comparison. The format of design in 2013 involved two distinct projects, one detailed and another conceptual. This was rather different to the single, but multi-phase approach experienced by the participants of my study.

Among the notable aspects of my experience of design was the 'build-up' to design in the years preceding it. There was an emphasis placed upon design by lecturers, senior students, and peers. Another notable aspect of design was the interactions I had with my peers during design. These interactions by and large led me to the Grounded Theory approach to explore this substantive area, precisely because my experience of it was complex and a significant aspect was social. An example of the complexity is those centred around group cohesion. I recall attempting to cultivate group cohesion by suggesting socialisation 'outside of design', however these did not come to fruition. I also sympathised with students' accounts of feeling isolated at various times in design, as well as the prevalence of the chief processes in this study: comparing and constraining.

Another aspect of this study that is noted here is my own involvement as a graduate tutor for several modules that the design participants took prior to design. A significant module is the fourth-year module CP409, for which I was a tutor for the Problem-Solving portion of the class. Through my engagement in this class, I gathered an insight into students' interactions with one another pre-design. My informal observations of students moving around; speaking to one another; sharing solution strategies; huddling around computers; diffusing from one group to another - all lead me to believe that I was dealing with highly socialised cohorts. This informal observation influenced the research design, such as opting for interviews over focus groups, and were substantiated by many of the students' interview comments.

While undertaking the observations of supervisory meetings and conducting interviews, I also had many informal interactions with CE design students (e.g. in corridors), in some cases students, unprompted, would share their experiences of design. In one example, an observed group carried on speaking to me after a particularly challenging meeting where their adviser had been quite critical about their progress. I entered the computer labs alongside the students and noticed various behaviours such as group members scattering to different sections of the room; some students in the room approached to listen in to the conversation I was having with one of the observed participants. In another example, a student unprompted, discussed what would become the major emergent process of comparing. This student described the feeling of his "heart sinking" when they glanced over to a peer's computer screen and saw that they were doing something different to their own approach.

Finally, in 2019, I joined the chemical engineering department as a teaching assistant. As part of my role, I have been required to supervise multiple student groups as part of CE design including, more recently, distance learning design projects. This new experience allowed me to be a participant observer, although no formal observational fieldnotes were made, as informed consent would have to be obtained. With this new perspective, as a supervisor, I was able to further contextualise my findings, provide practical advice to the groups based on my findings, and observe how students viewed the advice as additional, informal data for the study.

Chapter 5. Emergent Findings and Analysis

5.1 Introduction

The chapter presents the salient codes emerging from analysis of transcripts from interviews conducted with the study participants. The chapter begins with codes that relate to pre-design conceptions to demonstrate the social setting and norms of the participants under study. The chapter continues with an analysis of codes relevant to the design brief (including the brief and evaluation criteria) followed by a discussion on significant aspects around the design supervisory experience. Then an analysis of the technical aspects related to design are covered. Students design practices are explored in significant depth as it relates to the design experience. This is covered first by consideration of the group phases, followed by the individual phase of design. Finally, the chapter closes with a summary of these salient codes.

In this chapter, the reader will note the use of lengthy excerpts of data. This is deliberate and intended. It is understood that by including excerpts which capture detail that two main intended goals are achieved. First, by doing so these address what Walther et al. (2017) describe as maintaining "the meaning constructed in the communication community throughout our analysis" and hence, is a means to more dutifully serve the participants and wider community of students and staff. Second, it is felt that the analysis must demonstrate rigour and with the inclusion of detailed quotes, the reader is able to obtain a greater understanding of the meanings from which analysis has emerged. With a clearer understanding, this offers the reader to make more evaluative judgement of the analysis itself. The analysis often makes use of multiple excerpts to demonstrate the prevalence of the findings and also occasionally incorporates single narrative accounts that give a rich insight into the design experience.

In general, all excerpts have been produced verbatim, errors in grammar and styles of speech have been maintained as these were stated. Occasionally additional context will be provided in square brackets. The words of the interviewer are placed in bold to distinguish from the interviewee who is labelled following excerpts. Any information that would identify individuals have been omitted in the interest of preserving anonymity.

5.2 Situating the Design Project in the Programme

Students entered into CE design with the prior experiences and socialisation gained through their programme. They also attached significant importance to design; associating it with "real engineering", contrasting this with the primarily "taught" modules that largely made up their programme.

5.2.1 "We're Close": Pre-design Socialisation

Participants interviewed suggested that a significant factor of their degree programme was the highly-connected and sociable cohort that they belonged to. This ties in with multiple students' positive assertions relating to the highly socialized cohort.

> I don't know if it's just because of my year, as a year, is really quite close. We all do things out-with uni. Like we'll arrange a Christmas night out and sub crawl and all that sort of stuff. - *Sarah French*

> [Laughs]. Good… I guess. Sometimes I'm like, "should I have studied something else?" But then I've made really good friends and that's helped a lot and we do help each other a lot in our year. Which is good. It's been enjoyable. - *Iona Mitchell*

> So, I was speaking to them and then other people were speaking to them, and then I get invited out to things – just from that… Everybody, I think it's because everybody's in the one place at the one time all the time – everyone's working in different groups of the time, everybody socialises together. - *Ellis Donaldson*

> Everybody is so, so – you can approach anybody and I think because we are such a close-knit year group. It actually benefited, especially me, but everybody else quite positively. It's like, you can engage and it sort of helps you with your classwork as well. So, your friend group might not be able to get something – but somebody else will. And because we are all so close-knit, it's not like… What's the word I'm looking for… It's not awkward to go and speak to somebody. - *Phillip Easter*

> I've not - I wouldn't say we're like particularly close with many of them like as in really close friends' group wise, but whenever we've been in groups before or nights out and stuff I've always spoke to them. - *Ewan Murray*

Many students were connected through a wide network of friendships and acquaintances. Contributing to this sociability may be the prevalence of groupwork on the degree programme, often requiring students to interact with others outside of their peer group.

> And working with other people, the group aspect of it. I think – we do a lot of it in engineering and I think that's a good thing, because I think the group work has always been throughout the whole four years, the most valuable stuff that we've done - *Ellis Donaldson*

> Chem eng labs… I always enjoy practical labs just because you are working close with other people in the course and if they are not your mates, they'll quickly become your mates because you are working together twice a month. I actually really enjoyed labs – not what we did in labs – but I enjoyed the team or social aspect of labs. - *Cameron Hooper*

> But I mean, like group work had been promoted like every year we've been in here. So, I mean, if it's not like in almost every year I've had - someone - like five new people in my group. I mean, there's been a couple of times I've been with people that I've known before. - *Ewan Murray*

> I think the most positive things… The most positive part has probably been the way that everybody works together outwith what the lecturers give us and all that kind of stuff. I've definitely found that there is a sense of community, because everyone's feeling lost. - *Ellis Donaldson*

The degree of socialisation represents a conditional factor which influences behaviour throughout design. Much of the expectations and rules of engagement with the wider cohort is reinforced through the programme preceding the design project. Strengthening this highly sociable network was the various difficulties that the students have 'weathered together'. This experience of shared difficulty throughout the programme is a powerful social circumstance that, in the case of the years of design investigated, bonded the cohort.

Beyond the intra-cohort interactions, students also connected across years through social events, organised by the chemical engineering society. This is a student-led university society which primarily organises social events across all years of the chemical engineering programme.

5.2.2 "It Will Absorb Your Life": Ritualising design

The design project was a significant component of a student's education and its importance is highlighted at different stages.

> I was so… I was very scared. I've never been as scared about exams as much as I was about the group projects because it's a big… Ever since you went into third year, there is a big thing about this project you do in your second semester fourth-year. Everyone is just talking about that. And even after my third year. Some of my projects that I was doing in university, like lecturers kept on going "wait till you do your fourth-year project". So, there is a… And it's 60 credits – that's *a lot* – if you do well in that, that… It can set which class of degree you're going to get. - *Spencer Jennings*

> We communicate with people in other year groups, my flatmate is in the year above. So when he was doing his project, I remember him struggling a lot and he was just doing one unit. And it was easier than our unit. But I remember thinking, "that's a lot of work!" - *Cain Bruce*

> I can't believe it's finished… That way, it's built up and built up for the entire of your time here, and then it just goes like that. - *Ellis Donaldson*

> Kind of – people talk. Obviously, you speak to people in the years before and they are like "mmm, design ?" [facial expression - concern/worry]… - *Iona Mitchell*

> I had heard a lot about how it was very stressful and how it's horrible and how a lot of people leave after fourth-year because they don't want to continue after that. - *Aman Chowdhury*

> So, one of my good friends is in the year above. So, she throughout the whole degree has been able to fill me in on what I've to expect, what's coming. Although things have changed year on year, like they had three phases, stuff like that. She was always giving me a heads up on what was going to come up and basically that it'll absorb your life. Design will take over, but you need to work as a group, that was one of her tips. - *Laura Dawson*

The anticipated difficulty of the design project is conveyed to students through different mechanisms. Students may have witnessed students undertaking design tasks in previous years in communal spaces. These observations provide students with perspective into design prior to their own engagement in the project and, to some extent, sensitise students' expectations of the challenge involved in design.

Students reported communication with senior classmates as another window into the design experience. The design project is alluded to as a great challenge from students who have already undertaken it. Furthermore, students also reported that academic staff expressed the importance and difficulty associated with the design project. These interactions indicate an effort to ritualise the design project to some extent and hence make sacred the experience.

The design project, then, was akin to an academic rite of passage which students must pass in order to 'become a chemical engineer'. As majority of the students continue their degree to obtain a Masters in Engineering, these students are reincorporated into the post-design group who communicate the importance and difficulties experienced as part of their design project experience.

5.2.3 "In Industry": Designing Professionally

In interviews conducted, it was observed that the belief that the design project connects to practice in an anticipated future profession had been internalised by many students. This complements the IChemE's suggestion that the "academic design project should simulate so far as is reasonably possible the real world, whilst acknowledging the constraints of the educational setting…" (IChemE, 2017). This simulation was alluded to by the design coordinator at the onset of the design project with explicit reference to certain limitations placed on reports, such as word or page limitations and concise communication, and interactions that could be expected between design groups and supervisors, such as shifting the role supervisors as instructors in learning to facilitators in design.

Professionalism is simultaneously an aim and a justification in the context of the design experience at Strathclyde. In general, academic staff and students agree that professionalism is important as a feature of the design project. Professionalism as a social construct, then, was used by staff and student to justify practice, behaviours and expectations around CE design.

> I think so because I got used to working in that kind of what will be professional setting, like you're working with other people to go towards a common thing. *- Sarah French*

> Especially if you go into industry, everything you do is done in a group anyway. No matter how much of a small project you do, there's always like two or 3 people involved. *- Spencer Jennings*

> Like part of something big, like a small presentation we've been doing, or even the design project we did last year was only 20 or 40 credits. Whereas this is 60 credits in one semester, so it's much more professional. *- Will Ross*

> I love it. Yeah, it feels a lot more like what the job could be. Which is nice. *- Cain Bruce*

> Before, we get an exam question that tells you everything you need to know to do it – we never really have to deal with, like, "what if you have a similar situation but you don't have two thirds of the data – what can you do to get around that?" *- Cain Bruce*

Among the features that contributed to the professionalism of design, students cited the organisation of groups of students and that the design task was inherently open-ended in nature. The breadth of the design task was also reported as a feature which made it more orientated to professional engineering work. Interestingly, the high-credit worth was also associated with professionalism as it related to the higher importance associated with the design project as it compares to the wider degree programme. In addition all students, with the exception of those on the ACCE programme, were solely focused on the single endeavour of CE design - perhaps further contributing to the perception of relevance to professional practice.

Staff and students demonstrated a mutual appreciation of the professionalism as part of CE design, however, this did not necessitate a shared understanding of professionalism. In some instances students appreciated that certain educational features of the design project aligned with their expectations of future employment as professional engineers, specifically around the design being group-based. However, other aspects of the design were perceived as being directly in opposition of students' expectations of professional design.

> Because in real design it would just be as long [in length] as it takes. - *Billy Reynolds*

> Obviously when we are in industry it'll be totally different – we'll actually have kinetics for our reactors and stuff like that. - *Cameron Hooper*

There were aspects of design which students perceive as limitations which arise from the educational context in which it takes place. There is an expectation that 'real design' in a professional setting enables the realisation of design solutions through the authenticity of the limitations and expected resources available in such contexts.

5.3 A Culture of Sharing

Student participants highlighted the importance of sharing as a deeply embedded practice that emerged from their experiences on the degree programme. The culture of sharing was one that manifested in different ways in the CE design.

5.3.1 "Have You Seen This?": Sharing as a normative practice

Sharing was one of the defining qualities of the collective cohort. Many interviewees discussed how information sharing was a typical occurrence within the student collective.

> I can be sitting in a group with someone and they'd be going, "oh, you've not seen this paper or this past paper on this" or whatever. So - and you'd be like, "Oh, that'd be really beneficial." And then they'd send you it or they've been told you know, "look at this book" by one of their friends and gets passed round the year and everyone ends up getting it. - *Ewan Murray*

> I always thought that this was people being stale, but if someone asked me for work, I'd happily give it to them. And trust them not to copy it word for word and get me done for plagiarism. I feel like it's the same for the design project. - *Cameron Hooper*

The proclivity to spread information throughout the network, especially that which related to technical tasks, was one of the distinguishing characteristics of the socialised collective. Sharing was not limited to information related to their courses but also included entire submissions of coursework too. Additionally, advice and guidance from tutors and lecturers were also shared and this was spread through the highly-socialised student network rapidly. While this behaviour appears to be altruistic, there was a transactional element to sharing which increased the likelihood that other students would reciprocally share in the future.

> So, yeah, some people are happy to share their work and some people are just like, "no, don't care. You're not seeing anything I've done." You know the kid who

> had his folders round his test paper – that kid. I feel like everyone feels like we're all in the same boat together. - *Cameron Hooper*

Although sharing was considered virtuous within the context of the student cohort and was generally a widespread norm, not all students participated in dissemination of their work, as discussed later in the chapter. Cameron Hooper's negative attitude towards such students demonstrates the perception of non-sharing members as violating this normative behaviour.

5.3.2 "Helping Each Other": Collectivizing to Address Gaps in Academic Support

Students recognised peers as valuable sources of feedback and support in their learning where there may have been barriers to approaching academic and teaching staff.

> I think how difficult it is to have access to and speak to your tutors. For instance, in school it's so easy – they are always they're always willing to help you. What I've found here is that it is very difficult to, apart from your lectures and tutorials – and tutorials there are sometimes only one lecturer going around the whole class. It's so difficult to get help, getting help is so hard. I just ask around - people, and that's what everyone ends up doing, you just start helping each other. - *Frank Hill*

> I mean, I can ask lecturers and stuff but they're busy people who may not be able to help you directly. But I mean, even if there's not like people in my close friend group, if I say to someone that I've even just been put in a group with, you know, "I'm struggling to understand this aspect", they will help, they will openly try and get you through it… In the vast majority of cases if you ask for help, and your years very willing to help you, at least I've had that in my experience. - *Ewan Murray*

Contributing to the cohesion of the cohort is the perceived lack of accessible support from tutors and lecturers throughout the programme. This accessibility of support relates to both the ratio of students to tutors and also perceptions students had related to approachability of tutors and lecturers.

In the absence of formal academic support students supplemented this through alternative support mechanisms. As a result students report approaching peers for support when facing challenges and difficulty related to coursework. Requests for support are responded to with assistance, or forwarding those requests to connected peers who may be able to assist. The collective knowledge of the cohort acts as a proxy for tutors and lecturers - offering the wealth of information held by the individual students that comprise it. These norms and behaviour related to approachability of peers carried into the design project.

5.3.3 "The Years Above": Connecting Across Cohorts

Students not only shared information sourced from their cohort, but obtained and disseminated information from senior students on the same programme.

> So, some people know people that were in the year above, say they went to their school and then they're doing the same course so I've not been fortunate in that position and no one in the year above me came through Strathclyde through this. But I know people from the West of Scotland, or whatever, they've got friends in the year above or the year above that. You know? - *Ewan Murray*

> A couple years above as they had done the same one. Obviously, we all had their work because people share.. - *Sophia Duncan*

As well as connecting with peers within their cohort, students also connected across cohorts. Students shared experiences and accounts from senior student. Additionally, students also obtained solutions from students "from the years above" and, owing to the norms around sharing, these tended to be distributed among the cohort.

5.3.4 "Cracking the Code": Distributing Pioneering Work

Cain Bruce describes a phenomenon related to his experience of technical challenges faced in the degree programme.

> Yeah. That's how like higher University courses went… Some person cracks how to do it. And they just get bombarded with people asking them how to do it. And that's when I start using the word "unfair". And it's not I'm the one cracking the code by any means. But if there's somebody who is doing really well and they crack this thing and then everyone else asks them and they are nice enough to help – it's nice that they help but it's also the fact that if they all get the same mark, then… Is that fair? Because one of them did the actual legwork for it and then just all their friends, so they also… I mean, I've taken those hints when they've came, when I'm really struggling with something. And they are helpful and I'll thank those people for the rest of my life for their kindness in those moments. - *Cain Bruce*

Cain describes, in his view, a recurrent pattern around individual 'pioneers' who solve a given problem in the educational setting, ahead of their peers. Friends and, if relevant, group members become aware of those who have managed to solve a challenge and subsequently requested access to their solutions or new found understanding. Cain mentioned that "they are nice enough to help" but alludes to there being little choice in sharing given how deeply ingrained a practice it was among students. There was an expectation, most likely owing to the sociable nature of the cohort, that these pioneers disseminated solutions to friends who distributed these to the wider collective through their networks of contacts. Cain struggled to reconcile the help he had received from such students and the resulting similarity of achievement in grades. In the context of the community of students, the individual reward is forgone to benefit the wider collective.

5.4 The Design Brief

The design brief and accompanying assessment marking criteria information is central to student and staff activity and concern and was invoked often in the context of supervisory meetings. These documents were among the only central communications to students and staff and hence were assigned significant importance by those involved in design, supervisors and students.

5.4.1 "Playing by the Book": Orientating to Evaluation

The main design requirements were conveyed to students through the design brief and accompanying marking criteria document. Since these documents provided students with an idea of how assessment would be carried out, these documents were used in orientating to the design task and as a means to organise group activity.

> That was just more to tie in with the actual project brief to make sure we are following the brief the way we should have been. Do you know what I mean? - *Sarah French*

> Because you have the marking scheme as well so you can sort of argue like "I think we should include this because of this" and if someone disagrees then you kind of put the onus on them and say "why do you think you should include it?" - *Billy Reynolds*

> I don't think there was that much of an incentive, I don't think there was a scope for is creativity. Because the page limit was low. So to do a paragraph on something that wasn't mentioned in the marking scheme that we were given or the marking guidance would have been crazy because you would be taking away words from things you knew were being marked. - *Billy Reynolds*

> The design stuff… The marking scheme is quite scary. When they say stuff like, "if you fill the brief completely, that'll maybe get you 65%". If you hit everything in the brief completely, that'd be like a 70%. Which is… The expectations are high. - *Cain Bruce*

> Obviously, we used the brief quite a lot. Well, we did at that point because that's what you're getting marked against essentially. So, we'd look at the bullet points and ask, "have we ticked that off yet?"; "What do we need to do to tick that off?"; "What do we need to do?". And that's how things like "Oh, no one's got the hazard

> and safety yet, we need somebody to do that," that's how that came about rather than someone just coming up with jobs in their head. It was all, mainly structured by that. - *Cain Bruce*

> Yeah, possibly… Because some groups have done the process fully continuous – but they've just got really, really small capacity. We could have done that as well, but we wanted to make – there's a lot of waste from continuous. So, we didn't want to do that, because in the brief, it says you got to make a sustainable, minimal waste… So you're not going to pick that when that's what the brief says. Even though that would have helped is more, because it's continuous. - *Iona Mitchell*

> Playing by the book, actually. Just going through the marking scheme, it's the first time I've ever done it. Literally just gone through the marking scheme and being like, "have I got that, have I got that, have I got that?" So, I went through the marking scheme- me and Haiden- and wrote our design brief for our thing. - *Cameron Hooper*

The design requirements outlined in the brief were used by students to focus their design activities. These requirements were often invoked as a criteria for deciding worthwhile pursuits throughout the design project. These documents also guided their division of labour with respect to the group elements of the design task, as mentioned by Cain. Billy and Iona used the requirements outlined in these documents as a criteria for informing their design decisions. Many students used the brief requirements and associated evaluation criteria to "play by the book" and "tick off" requirements that were defined for them.

The design brief and associated marking criteria were vital documents in relation to students' design experience. Given that the design project took place in the educational context, the success of the design project is associated with meeting as many of the requirements which contribute to a good assessment relative to the marking criteria. In this sense, students in CE design generally adopted a pragmatic approach to design by deferring to the academic context.

These design criteria became foundational sources of stability in the design experience and helped to constrain the open-endedness of the problem. It follows, then, when these stabilising requirements were either ill-defined, contradictory, or subject to change that this drew considerable concern from students.

5.4.2 "A Bit Wishy-Washy": Clarifying the Brief Requirements

As noted above, the brief was central to the design project and it functioned to direct students' activities as part of the design project. Areas of ambiguity in the requirements set out in the brief, then, were points that students gravitated to often for clarification.

> Because the brief is a bit wishy-washy and they seem to change it… Like the peer-assessment wasn't done and something else got changed. - *Cameron Hooper*

> We are asked to do quite a- design something, design this, can they not just have everything we need to know before we even start. Why are they letting us, why are they 2 weeks in "oh, you mentioned that you can't include this…" or "it's not part of your thing" or "it is part of your thing". And then you're hearing ones [sic] from different people and it's so confusing. - *Frank Hill*

> Oh, well that was down to the brief because the brief wasn't precise enough. There were bits that it got pulled up a lot through the project. Yeah. So, a lot of the class reps had to speak to the head of the department. Yeah. - *Emelia Emese*

> Again, because they told us we had to do – this is another thing for phase 2 – the brief says one unit and then we come into the meetings, they say "no, no, not one unit, every single unit, you're to-do." Pumps, heat exchangers, condensers, everything. And we were like "do we really need to do this?" – "Well… Yeah." - *Ellis Donaldson*

> But the fact that the brief was actually quite different to the email they sent out in terms of what they're asking for, to the people who read the brief cover to cover when we first got the thing and were planning that, how it was going to go, then to wait until after the start after the start of phase two has begun to then change it and send out I think it's a bit unacceptable. - *Will Ross*

During the design projects, areas of the brief and marking criteria often require clarification. However, in some instances specific aspects of the requirements included in these documents were changed significantly. Since students attribute significant import to these requirements, when such changes were made these were generally met with opposition. Students tended to demonstrate greater opposition to changes that were perceived to impact their design negatively.

Given the open-endedness of the task, design requirements defined in the design documents were thought to be the most "objective" and "fixed constraint" on the design task. When students observe that these were modifiable, their frustrations were associated with an unexpected open-endedness that emerged in the design task, especially where these were believed to be unequivocally fixed. This gives rise to great uncertainty, even though it offers some advantage to students to negotiate the requirements set out in the brief.

5.4.3 "It was Surplus": Compromising on Quality to Meet Design Requirements

Many students reported difficulties associated with certain brief requirements restricting the design task - one that was reported most often was prohibitive limits on content length.

The construct of professionalism was invoked in some instances where students observed incongruity between the constraints of the academic setting, both intentional and unintentional, and their expectations of professional engineering.

> Whereas it did seem a bit arbitrary at points. Especially like the economic analysis when you're told "it's only… in industry they are like 1000 words." but they are not. There are many many pages because if you're going to spend $1 billion on something, you're not going to summarise it… The abstract of the report would be 1000 words, not the… And I know it can't be that long, but still, it's a bit like… - *Billy Reynolds*

> And then like, but it's a good graph, like one of the guys spent absolutely ages doing all these things on market data. Couldn't put it in, because it was surplus, it wasn't in the brief. So, we just had to drop it and I mean, I thought that would be a very good thing. Because we're trying to sell this as a feasible design, so you want to know if the markets going to be good. - *Ewan Murray*

> I understand that if you've got a manager whose not got a lot of time and he wants 10 pages, it's got to be precise. Yes, I absolutely agree. But, to make six people's work for three weeks solid, 8 pages – because once you include references of two pages, it becomes 8 pages. I feel like our report really could have given us an extra two pages or not put the references in the ten pages. I really feel like our report could have been pretty excellent. But it wasn't. Because we had to take out so much stuff. And then you're kind of like, "what do I take out here?" I need to take out something but I don't know what. And then you take something out, but it's kind of important so you put it back in. You realize you've taken out nothing. So then you're taking out stuff that you know is important but it just has to go because you don't have space. - *Cameron Hooper*

Some of the tensions in design arose as a by-product from the design taking place in the educational context and students were sympathetic to some of these tensions (e.g. lack of data). In other areas which were perceived as amenable to change (e.g. report limitations), professionalism was favourable. Generally, students adapted their behaviour to meet this requirement while others used professionalism as justification for proposing changes in the design project to closer match their expectations of professional work. This was communicated during design meetings frequently, with many observations around how restrictive students found the report length in particular.

Others, such as Will Ross, observed that excessive limitations on content length resulted in a tension within the academic requirements of design.

> Whereas we had about three pages worth of references for all the stuff that went into phase one, which we had to cut down to half a page or so. Which is - it's a bit counterintuitive because they want you to use they want you to reference your work. We cross referenced and we cross checked our sources to make sure it was right. And then we weren't able to include that in the report to demonstrate that we've done that work. Okay, so it doesn't always make sense to be so strict. - *Will Ross*

Will outlined how the limitations were 'counterintuitive' as these resulted in the omission of content that was otherwise required both from the brief and the academic context. As a result, Will reports, his group were inclined to omit references for the sake of the brief requirement. This evidences how constraints on design can impact the authenticity of design from both an academic and professional perspective.

In some instances, students would not compromise on their design, despite the requirements, and others reported that the brief requirements were too restrictive to overcome.

> I knew there were people submitting so I actually ended up getting the distillation column by picking it out of the hat and then I was talking to other people in different groups who were doing distillation column, they submitted their project… Because some of them submitted a day before the submission date and they submitted it like 3800/4000 words. Even though it said 3000, they submitted it with those many words and they said there was no way for them to get rid of any more words. - *Spencer Jennings*

> Well, we even asked, we were like "what's…" At one point we asked our supervisor, "what's the penalty of going over the page limit, would it be a bigger penalty to go over the page limit or cut stuff out?" But then they were like "if it's not in the page limit, if it's not in the page limit, it doesn't even exist." Because it was stuff like, your references had to count in your page limit. That was the most annoying thing. Because they take a huge amount of space. But you have to reference everything, so then, if we did that, references… It would be like, we hadn't referenced anything. For goodness sake. - *Natasha Douglas*

> And I read through my report again going "I really haven't shown the best of what I've done." Because I was trying to get in basics… I think the page limit for phase 2 was harsh. I really do. I think last year, they may be had the same page limit, but they had unlimited appendixes and that made it easier to get across everything that

> you wanted to get across – even if you can put it in the main body of the report, but five pages for appendixes… And the references included in the page limit is just, just scraps hold two pages of your page limit. It should have been 12 pages, but it was really 10. Because you had to have all your references. I feel like that encourages people to not reference, and that kind of seems wrong to… Encourages you to not include things because… All we had were two pages of references and had to cut it all back. In phase 1, we were just hacking out references [laughs]. It was mental. - *Ellis Donaldson*

In some instances, brief requirements were considered too restrictive that students opted to violate the brief requirements. Spencer reports classmates submitting work that exceeded the content length limits owing to the inability to remove further content. Will, Spencer and Ellis' comments allude to the tension that existed in students demonstrating the quality of the work they produced and meeting the brief requirements, with Spencer specifically suggesting that he knew of people submitting beyond the word count - and possibly risking academic penalties.

5.5 Negotiating Design Supervision

Students met formally with supervisors each week throughout the design period. These meetings had no set format and therefore there was variability in the structure and format employed by students and staff as part of the supervisory meetings. Some of the significant features of supervisory meetings was the somewhat conflicting roles held by supervisors and how supervisory meetings were sites of negotiation of the design requirements.

5.5.1 "It was Subjective": The Supervisor as the Client and Evaluator

Design requirements did not solely emerge from the project brief, but from a number of sources including the evaluator of students' design projects, who happened to be the students supervisors. Supervisors were often interpreted as the academic "client" of the design project. This arose from the context of design, where the academic assessment was the measure of success of the submission. This aspect of the supervisory role of being the primary "customer" of design was reiterated by all students, demonstrating that students aligned themselves to this educational constraint.

> One thing- I'll just go and tell you about it. Basically, the thing with ibuprofen was that we could assume it was converted in the body and there was an isomer that we produced that wasn't a huge amount but Emma [supervisor] touched on it and I said to a few people in my group, two of them, I was like "you need to find this reference and reference it in the thing. I was like, please can you do that?" - *Frank Hill*

Yeah, translating the brief we had for phase 2 – it was quite open-ended on some things and we'd ask in the meetings with your supervisors, "or, should I do this?" But, they would just say "it's up to you" and then that was open-ended. So, I suppose that shows how far you were going to get your marks but you were never really sure what was necessary – I thought that was difficult. - *Sophia Duncan*

So, I think that's why it was good because we weren't doing – some things we did do the same, but at the same time other things we did do differently. Because… Because, obviously, your supervisors – what they wanted… - *Natasha Douglas*

It's Dr Viola Greco [supervisor], who I didn't have any experience with before. I think she's relatively new to the department. We've had one meeting with her and she seems fine. No idea, how good a marker she will be but heard her exam for the year above was quite tough this year. - *Cain Bruce*

So then, I'm not sure how the marking system works, but I think it's peer-reviewed thing, where another marker will mark – like, two markers mark each bit. So if somebody that's told their group to do one unit, gets my report… Will I be marked harsher for that? Or will they be able to speak to my supervisor and understand that was what we were told to design? And likewise for some people who get my supervisor marking their part, is very much all about keeping it all consistent, that's one really aspect of the design – the very example that he said not to do – if they had that and the report, are they going to get marked harshly for that? - *Cain Bruce*

It would be nice to get a good mark, it really depends on what Hodgson [supervisor], because I think a lot of lecturers have different things that they look for. Hodgson could be very focused on the PFD, but I don't think she will be, I think, surely more focused on the plant location, stuff like that. - *Frank Hill*

So, some supervisors were wanting really creative things, some supervisors were wanting really technical things and I think it just depended on who you had and how they got marked based on what they wanted – it was subjective. - *Laura Dawson*

So, yeah, I feel like everyone is talking about – "who is your marker? Who have you got?" and they go "oh, you got a good one." Everyone is humming and hawing about who they have as a marker. And also, now we have to do the control over a reactor or whatever it is – we have to put a control system in and we've got [supervisor], who taught that class, he taught process control. And I can just tell he's going to have his head in his hands when he reads mines. - *Cameron Hooper*

But I had no idea if she knew what we wanted in it. It was all very vague. And then to put that all into ten pages on the basis of "a manager wouldn't have time to read it." He would have told you exactly what he wanted in it. "Can I speak to your manager for an hour, one-on-one and ask him this, this, this" and he goes, "yes, no, yes, yes no." It only takes 5 minutes. But it was like, "whatever you think goes in." I was like, I get it – "you want us to think about what goes in. And we have, and we still don't know. So, can you please help us." It was a [response of], "no, no- and if you have and you still don't know, think about it more." And then you obviously, make that judgement yourself which I suppose, good call – learning curve. But when your grades getting penalised because of something you genuinely didn't know and they wouldn't help you on it, I feel like it's a bit unfortunate. - *Cameron Hooper*

> Emm… So, we – ours was fine. Although, it was so different – we had been told from the start that you can't ask questions explicitly. But then, again, there was this, "oh, this supervisor said this." There was a lot of discrepancy between the supervisors like, what they were looking for. Which, again made it difficult, because "maybe mines just forgotten to mention that they want that as well." But the meetings were good. Some people were really poor, they didn't talk. But that just reflected badly on them. - *Laura Dawson*

> Just like – I feel like I started asking loads of questions in the meetings to try and gauge their thoughts on some things. Because, you knew you were going to get a straight answer so you could just kind of see what they thought. Even things to do with materials, wall thickness – just see what… Here's a good example, when I was asking about, "should we be sizing the nozzles and the pipes that draw off your main unit?" And then, I asked Dr Fraser [supervisor] about it because I thought that would be a big part of the design, but then he came back and said, "well, your chemical engineers not mechanical engineers – why would you be sizing all these pates?" And that kind of drew a line under that issue for me. - *Sophia Duncan*

Students reported this dual role held by supervisors as both "clients" and educational "evaluators" of design. The extent to which students believed that requirements conveyed by supervisors in their role as clients were accounted for during the evaluation, the greater the certainty with which students were able to commit to decisions based on those supervisory interactions. Observations of these interactions were made during supervisory meetings. The degree of explicitness with which these requirements were conveyed to students influenced how students prioritised these. Additionally, as indicated by Cain Bruce above, the certainty that the supervisory requirements, translated into evaluative requirements which added an additional dimension to the sourcing of requirements.

Some supervisors were less inclined to provide statements of requirements and would place the responsibility on the design group. However, this approach was criticised for its lack of authenticity when compared to the professional context.

Prior to design students may have also engaged with supervisors through taught classes. Through these interactions, there is an assumption that supervisors have ‘different things they look for’, owing to classes that supervisors have taught or research the supervisor had conducted (as reported by Cameron). Students also reported categorising supervisors as lenient and harsh evaluators. These perspectives arose from prior interactions with supervisors but also through information obtained from senior students who may have been supervised by a specific academic. Some students, such as Natasha, were reluctant to ask questions because it may demonstrate gaps in her knowledge.

> I dunno, I just get quite stressed. Like, “oh, can I ask this” or getting them to understand what you’re trying to ask. And then also when they – I’m just like “I don’t know, should I know this?” or not explaining it properly. Because they’re just going to say something like “oh, you’re completely wrong.” Which, I know you’re not meant to be scared of because that’s what they’re there for. - *Natasha Douglas*

These student perspectives suggest that supervisory commentary on developing designs become a source of additional requirements that are placed on students. Since the interactions are much more spontaneous than the pre-planned design brief, there arises much more variability of requirements. These could at times, contradict the information found in the design brief. In addition to direct interactions with supervisors, students also indicated that their prior experience, and information from previous years’ students, that some supervisors were characterised as being “good” or “bad” markers - students associated the former with leniency and the latter with strictness in marking.

5.5.2 “Too Specific”: Seeking Explicit Feedback & Expectations

In light of the open-endedness of the design task, a oft-reported concern for students was to obtain feedback and expectations on progress in order to constrain the design task and outline supervisory expectations.

> Okay… Hodgson [adviser], as I say it is decent, she could help – she helped as much as she could. It was a bit frustrating at times because obviously they can’t say “yay” or “nay”. - *Frank Hill*

> I don’t even know… Casey [adviser] knew… Casey could tell us what she expected exactly, so that meant that we knew what to put in our report. But Curtis [adviser], when you ask him what he expects, talks to you for half an hour… And you’re like, “I don’t have half an hour to put in my report! I just want to know what you expect.” [Laughs]. - *Iona Mitchell*

> Again, the way that various advisers were to their groups – so, there was an instance where one of my friend had an adviser and in his meeting with his adviser,

he would ask – I think he was doing the crystallisation, so the purification stage of the process, and he would say to his adviser. "I'm stuck on this solubility curve" and the adviser, point-blank said to him, "that's too specific for me, I can't help you." Which, you shouldn't… Fair enough, it might be too specific for them – but, why are we getting a project that there can't – all the advisers can give at least a little bit of support to each of their groups. So, he walked away from that being like "well, why should I go to the meeting? Why should I be having meetings with my adviser that can't help me?" - *Phillip Easter*

They weren't especially helpful because I can understand the idea that you shouldn't be told the answer but then I think that it would have been helpful to be told what kind of answer they were looking for. - *Billy Reynolds*

I found lots of things challenging [laughs]. I thought in the feedback sessions that we had with our supervisors, I thought it was quite difficult to ask nitty-gritty questions. Questions about the actual design that you were doing because sometimes you wanted their opinion to know whether to go ahead with it or not – whether what you're doing was actually correct. - *Sophia Duncan*

One avenue through which feedback is sought is via interactions with supervisors during meetings. Since students orientate to supervisors as evaluators of their design, this feedback informs students' validation of their progress, thus constraining the design task.

So, like, when I spoke to Peter, I was like, "I can't find any kinetics for my reactor. Like, I can't find anything"… I was like, "is it okay, if I just use my patent conditions and try to work back and get some kinetics?" And he was like, "you can do that, but you've not got a lot of validation to see if it's right or wrong." And I was like, "I can't get any validation if it's right or wrong, because I can't find anything else." And so, then it was like, back to the drawing board, going back and just looking again, and again and again, through more and more papers and stuff. - *Ewan Murray*

Often, however, students' requests for explicit validation were dismissed at supervisory meetings. Owing to this outcome was the general instruction that, as stated in the brief, supervisors could "advise [students] on how a problem could be approached and which issues may be important but not expected to provide [students] with any details about how to solve a specific problem". In some instances, supervisors justified not providing validation of ideas or explicit expectations of ideas with the rebuttal that this would be "too specific"

I don't think that Dr Ohlson is capable – I don't think he's going to answer us tomorrow, so it's going to be interesting to see what he says. Because I feel like, what he's going to say is "that's too specific" or "that's up to you." And I know that they can't be, but I think, you need to – for goodness sake, you can see it – it's not

> like it's going to affect us that much. And they are there to help us? Do you know what I mean? And at the moment feels like they're not. - *Frank Hill*

Some students, such as Frank above, reported his questions and requests for feedback being met with excessive dismissal. This was found to be emphasised as a significant challenge. For students such as Frank, this brought into focus significant challenges in developing an understanding of the supervisory role and how it fit in his experience of CE design. Since this avenue for feedback was restricted, Frank Hill obtained feedback and expectations from alternative sources such as similarly-tasked peers in other groups (discussed later).

5.5.3 The Rumour Mill: Comparing Supervisory Advice

Students often obtained supervisory advice that could be highly subjective or contradictory and, like most design related information, went through a process of sharing and comparing by participants of CE design.

> Because Peter [other supervisor] gave him an idea. Peter said, basically, you can model it as a reactive distillation column. If you assume that everything below the feed point is a CSTR in series and everything above is just, flash tanks. So, if you did that, then you'd be able to… That's a good enough simplification to model it mathematically on Mathcad or something. That's a really good idea, hats off to Peter for that idea, that he is then giving his chance to go off and do it. Because Gilbert [Will Ross' supervisor] didn't give that to me. That's the magic that Peter Ingram has, is that he can think of stuff like that and… it's not a fair representation of my ability or my friends ability to chem eng. So, supervisors contribution to the project – there was a lot of disparity. But, at the end of the day, if this meant a lot more to me for my grades, than it does, I would probably be annoyed. And I might say something more than I have said to the class reps. - *Will Ross*

> Their concerns? I'd probably say the most valid thing that people have complained about in regards to the design project, it seems to be a lack of all of the supervisors being on the same page. Which, part of me enjoys that, part of me enjoys that some people are getting told to do slightly different things. Which means that you're not getting all the reports being exactly the same. But the other part my brain is "we are all getting assessed on this, and if one thing is harder than the rest, that's not really fair." - *Cain Bruce*

> So that's, oh no, yeah the negatives has been the uncertainty in what they're expecting. And the mixed signals and the supervisors isn't - I think it's unacceptable to be honest. I know they want different things. - *Will Ross*

> And it was good for keeping track of time but I think it was quite unfair because it seemed like some supervisors were sort of saying “you should do a lot more than this” whereas other supervisors were saying “well, I could advise you”… - *Billy Reynolds*

> I don’t know whether the way it’s been set up so that the supervisors can have freedom with what they want. But that’s the way it’s coming down. - *Will Ross*

> It doesn’t have to be “do this, do this, do this” because that’s not going to help, but if you know the parameters, then you can work within those parameters and like I say, some people are going to get better marks than others. Anyway. So, it’s just how well you fit the things that they are asking you to do, but if they’re not clear about what they’re asking you to do, it opens up complete… Subjectivity. I think each supervisor feeds into it a different thing. And again, that’s probably natural – but again, that’s where moderation helps. - *Ellis Donaldson*

> Because everyone has different preferences – all the supervisors – it was literally like a rumour mill. You would talk about stuff with everyone, like, “I don’t know if I’m going to do this.” And then someone would say, “oh, my supervisor says you must do that.” And then we’d be like, “oh, well ours didn’t say that.” So, you just never really know [laughs]. - *Sophia Duncan*

Supervisors primarily functioned as advisers to design groups. The extent to which supervisors advised their groups, however, differed considerably. Some supervisors gave explicit advice on how to overcome certain problems, whereas others provided more ambiguous advice with some even rejecting to offer any advice at all.

Amongst the information shared by students is that of advice sourced from assigned supervisors. In this case, the information is grounded in the academic context in which design takes place, but could impact technical aspects of design. Students had conflicting ideas of how designs were evaluated with some believing that supervisors took account of their own advice when evaluating, and others working under the assumption that the report would be marked without regard to supervisory advice. Nevertheless students compared supervisory guidance to identify differences that would create what was perceived to be unfair advantages in assessment emerging from contextual factors. Students used their understanding and expectations of the academic setting to constrain the potential ambiguity in the assessment.

There was competing expectations, evidenced in these excerpts, around supervisory assessment of students’ design solutions. Students anticipated that assessment would be objective and detached from interactions that took place at supervisory meetings. On the other hand, students actively sought out supervisory preferences to focus their efforts. From this interpretation, differences in supervisory experience were perceived as an incongruity between the intent of design and the academic setting in which it took place. This perception of unfair disparity in supervisory assistance is understood to be a contextual factor that has deviated from an anticipated norm. Students are then not simply subject to constraints emerging from the academic setting but attempt to constrain the context with their understanding of the academic function of the design task. Class representatives indicate a formal route to constrain the context from deviating significantly, but supervisory sites were also observed as sites for negotiation of constraints.

During supervisory meetings it was observed frequently that students would pose what they had heard from other groups regarding supervisory advice and assistance, for comment from their supervisor. Often, such presentations of supervisory advice was a means through which students could negotiate their design requirements.

5.6 Working within Technical Constraints

Since students were completing an engineering-based design, they faced technical issues when engaging with design in general, specifically around the technical limitations surrounding the specifics of design and their own expertise.

5.6.1 “Spending Two Days to Get One Value”: Lacking data

Generally, insufficient data and information was an oft-reported challenge, with students spending considerable time searching for ‘missing pieces’ in the attempt to address gaps in emerging design solutions.

> Before, we get an exam question that tells you everything you need to know to do it – we never really have to deal with, like, “what if you have a similar situation but you don’t have two thirds of that data – what can you do to get around that?” - *Cain Bruce*

> A lot of it is really time-consuming, like working out the numbers. I don’t feel like the work is hard, I feel like if everyone had all the data, you could do the detailed design in two weeks. Because you had to spend so much time looking for volatilities, and boiling points, and viscosities, it takes ages. - *Cameron Hooper*

> Which was quite good because I don’t know, it was for all the other pieces of equipment for crystalliser it was quite general. Like all the information, there wasn’t anything really specific on how to do it. There was crystallisation of ibuprofen, but there was nothing like how to design a crystalliser for ibuprofen, so it was quite hard. - *Natasha Douglas*

> We were helping each other and stuff… And that was good, that was great. Literally, we would spend two days trying to get one value. Because there is no information online, we had to figure stuff out. Which, I kind of liked… - *Ellis Donaldson*

> And Professor Kerr said that she'd looked on the internet for a couple of hours and decided there was plenty of stuff to work from. And we've all been on the internet for much longer than a couple of hours at this point and would probably disagree that there was a surplus of information, especially when you compare it to other design projects in the past, because when - when something's got commercial value the open literature is just not going to supply you with these things that you need to do a detailed design. So it's been quite stressful trying to get information and then information you can collate, which for a number of different sources, say for heat capacities. These abstract chemicals that we're making. There's not a database that we can use to find them, even knovel doesn't have the stuff that we need. So, having to use things from different sources and then working from that. When it's quite close to being endo or exothermic, if you use one specific heat capacity or the other one it can go either way. So then building on that. It seems like shaky foundations to build a house on. So, what can you do? *- Will Ross*

> When you speak to people that -like a not myself- every summer I got work at the brewery, really like people that have been at someplace like GSK. When they ever get asked to do anything by companies they just go on to like the online database or the one that the company's got or a program they use and they just type in whatever and the information they get, and it comes up. But with us it's just not been the case. *- Ewan Murray*

> And phase 2 – I just wish that… I dunno, I wish that the project had been more… there had been more scope for actually doing a good detailed design. Whereas, this stupid simplification I had to make because there wasn't… there didn't seem like there was anything else I could do at the time. I spent probably 3 weeks searching for a better way to do it and then had to go back to this rudimentary, unreal simplification. It was a bit of a nuisance and I invested a lot of time in the research phase that didn't culminate in anything good. *- Will Ross*

> But, you just had to make assumptions and justify them in the project. So, that was how it was overcome but felt slightly unfair that somebody could possibly, in the year above, have made a better job and a more realistic design of something because there was more information available on their specific topic… As I was saying, with activity coefficients I was like - there definitely has to be information out there, I don't want to assume ideality because it's wrong. It's wrong to do it because it's not going to happen. *- Phillip Easter*

Insufficient information was observed to be a recurring theme of observed supervisory meetings. Lacking data was among the striking challenges faced by students throughout the design project, however it was reported to manifest most significantly during the individual detailed design phase. This contrasts with the problems students have been presented with throughout the programme before design. Design itself involves a significantly open-ended problem statement with almost no upfront data provided.

The specificity of data required was associated with increasing complexity of the technical task. Often students reported expending significant amounts of time in the process of searching for data.

5.6.2 "Only Two Ways": Selecting Models for Design

Among students' initial activities is the search for existing processes which address the general design task as set out in the design brief. Students begin with a broad approach and usually narrow their search based on their research findings.

> People are trying to be different are trying to find stuff that other people don't know, but then you just end up googling for hours and not really getting – just getting the same information. So I think that was quite hard. Because I think for this project, it was quite – there was only two ways to do it, but then one way seemed a lot more prominent than the other. And there wasn't really any information about anything else, so everyone was basically using the same information. - *Natasha Douglas*

> They wanted us to do a specific process to make ibuprofen then, of course, we're limited from the patents, because where else do you get data from, how do you know what three steps of chemistry takes you to ibuprofen? There's nothing in a textbook that tells you… - *Ellis Donaldson*

> But there was also reports from previous years that got circulated. And then it was like, "who's got that one? That's a really good design." Like, "he's got that report, you should speak to him, he knows how to do that sort of thing." Which is helpful because it's good to have something to look at to compare what you had done. - *Laura Dawson*

> And I know now they are changing what the design project is every year, which I think I would have preferred because I feel like we had the same – what was it… Bioethanol… Which is done to death. And you sit there and you're like, "okay, so, here's this process that everyone's done before", so everyone just looks at old reports. They don't try and do something new, so it's kind of difficult even for yourself to innovate. Because the general process is always exactly the same and then you can't really change a lot of what's happening. - *Aman Chowdhury*

> One of our reactions was massively exothermic and another group had that it was endothermic, and it was like so polar. Theirs was like quite endothermic and ours was massively - like the most dangerous part of our whole process and it was quite

> the opposite from someone else and just because they used a different source to find the same information. - *Ewan Murray*

During the initial group phase of design, the similarity of problem statement leads to a shared, restricted design space. In this design space, there may be few evidenced or plausible models. When deciding on model appropriateness, students seek various factors to inform their choices, primary factors cited in this excerpt included limited available design models and availability of information required for downstream design.

The description of one criterion as 'prominent' implies a possible validation criteria by which students evaluate model appropriateness. The popularity of a given design solution or approach may indicate greater availability of related information which addresses a chief student concern around insufficient data for progress, as discussed earlier. Choosing a model with greater information availability is a form of preventative action employed to reduce anticipated ambiguity in future design tasks. This also translates to how students validated their own and other groups' design solutions - the more prominent solutions are associated with perceptions of higher quality. This also gave rise to significant tensions when competing models were adapted and students compared these, discussed later in the analysis.

Laura also mentioned that models were not limited to texts such as patents and published articles, but extended to design solutions developed by senior students during their design. Technical models are then sourced from a wide scope of sources ranging from the relatively objective (published material, patents etc.) to the relatively subjective (i.e. previous cohorts' design reports). A particularly rich excerpt comes from Cameron Hooper, who struggled with what was required from his design, if it was not based on models.

> I've still to do a multi-component distillation column which, admittedly, I'm probably just going to bash out from Crawford's (staff member) notes, because…This is the bit I don't get. People are saying, "we don't want you to go and do design – and do it out of the notes." Okay, but I'm afraid, that is how you design a distillation column. Like, I don't get it. Crawfor- no, wait was it Charley Hughes (staff member)? He was speaking to somebody in his group, he was like, "obviously, you'd do it, but it is not detailed design, it's just design out of your notes." I'm like, "well, I don't know what else you want us to do, what's the difference between taking it out of your notes or taking it out of Coulson and Richardson or an online source? You've taught us it because it works and it is true. I don't get why you want us to do anything else. And if so, why have you taught us that in the same year?" Because, the Crawford stuff was taught this year- multi-component distillation column. Yeah, it is literally in his notes in the first semester. And their always saying, "you won't get as high marks if you just do it out of Crawford's notes." I understand but what else do you want us to do? You can't make up design, if that makes sense. You can go above and

beyond- which I understand. But the way they said to not to try to use methodology- I just don't know what you want us to do? - *Cameron Hooper*

This excerpt carries much meaning, in the context of engineering design, and especially for chemical engineering. Cameron explained that he had learned approaches to design of particular unit operations, but was discouraged, based from information from another student's supervisor, from replicating a pre-existing method or model of design that he had been taught in the programme already. This throws much confusion about "what detailed design was" in this context, if not emulating standardised approaches, as he understood it to be. This demonstrates deeper procedural concerns around the ambiguity of design in a CE context. Perhaps, owing to this confusion is the inherent abstraction of CE design, as it does not entail the design of a physical prototype or concrete build phase.

5.6.3 "Two Weeks to Find Kinetics": Fixating on Model-Required Data

Finding relevant data to inform design is a key process that captures an approach students employ in order to constrain the emergent designs. Relevant data, which relates to the solution that is sought after, is then a form of *constraint* that students look for. Data, especially that which is published in some fashion, offers a relatively 'objective' constraint on design. Usually, sought-for-data is highly specific, especially when students base their designs on model solutions.

> Yeah, not entirely sure where to start. I mean, I think I know where to start, but, it's again, finding data for the stuff, that's tough. Quite a common feeling of I know, the six steps after the one I'm on, but I don't even have the data to do this one. So, I can't get the ball rolling. That's been the hardest part, is getting that… - *Cain Bruce*

> The lack of information was there was a lot of time spent searching for more and more information on it and using different sources. - *Ewan Murray*

> But I think the things that may have let us down was people's unwillingness to, if they can't find something they're just going to have to assume something and write it down. A lot of, "aw, I just looked for 8 hours for something" and look again tomorrow for 8 hours instead of just moving on and kind of… I think that was the problem. - *Frank Hill*

> Yeah, so I'm looking for like, oh, it took me pretty much two weeks to find a paper with kinetics for my reactor. And I've found it and it gives me kinetics. And I'm happy. But I feel that the last two weeks if I just had somewhere… that the University provided that they knew that I would be able to find just the basic information, not like, I don't need rate constants, I don't need equations, I just need

> to not have to spend my weeks looking for the heat of vaporization of ibuprofen. And that's just something really, really annoying. - *Ewan Murray*

The search for data can be unproductive and stagnate design progress, resulting in pressure for students to change the direction of the constraining process. Here, apparent constraints emerging from existing models can be subject to the tension of other constraints in the form of data, or lack thereof.

This suggests that the phenomenon of the constraining process is dynamic, with students attempting to fix and balance constraints emerging from the social and technical contexts in the various forms that those constraints may manifest. Often students prioritise model-constraints (or 'blueprint solutions') over constraints from the available data, which often results in an unproductive commitment to maintain the constraints emerging from the model solution.

5.6.4 "Don't Even Bother": Lacking Expertise

Students also reflected on how their technical competencies did not always match up with the complexities of detailed design.

> And then, the batch part of it – if we had been taught more about batch things, and how to consider them, or even how to consider a full batch process. Fair enough, we've considered a batch reactor, and we've kind of looked at batch distillation column, but we haven't looked at it on a big scale. Everything we did in design in third year – everything was continuous. To then be given something that was batch, so that was really difficult to work out to change. - *Iona Mitchell*

> Actually, for Sam in my group – he was designing a crystalliser and had no idea what he was doing. And I don't think anyone did, I think it's one of the hardest things to design, given that we've had no experience of them before. I don't know whose job it is to make sure we are all on track and that we are all getting somewhere, but a lot of the time that Sam was working on his crystalliser, he wasn't getting anywhere, and he didn't have anybody supporting or somebody to say "don't do that." Whereas in the other groups, Laura (supervisor) was saying "don't even bother trying to design a crystalliser" to people in her group. - *Will Ross*

> I'm detailed designing the carbonylation that actually changes stuff into ibuprofen, and I've never done carbonylation before. I've never really dealt with catalysts before. I've never really dealt with phasing before. I've never really dealt with proper separations, like separating stuff that's homogeneous and can't be in it and you've got to get it out. Most of the stuff I've never dealt with before in detailed. Like, there's stuff that I've seen and that has been mentioned but we've never done any

problems or anything like that. So, everything has been a new challenge to overcome. - *Ewan Murray*

And I mean, my bits hard, the section I've been allocated to design, I think is hard. But some of the other people in my group. Oh, thank God, I've not got like… Leon's been doing azeotropic distillation and a reactive stripper. And I was like "never have even touched on that stuff." - *Ewan Murray*

But I feel like I've never done a design project before fourth year. - *Natasha Douglas*

Much of design, specifically individual detailed design felt like unchartered territory for many students. Without established ways of working, some designs were considered impossible given their limited understanding, as indicated by Will regarding a comment about a supervisor cautioning against design of a crystalliser. Students reported that they felt that design seemed detached, to varying degrees, from their prior learning. Some designs were more aligned to prior learning such as was the case for Ewan and Natasha. Where there was recognised to be some similarity to prior learning, such as Iona Mitchell, this remained challenging for students to connect to previous concepts learned on their degree. This may also explain students' proclivity for designing those units with associated 'established methods'.

5.7 Group Design Practices

At the onset of the CE design, students worked in groups, and from the educational context this was encouraged by the overall group being assessed. Students engaged in many practices to manage and inform their group-based design practices.

5.7.1 "Flatmates and Grafters" : Knowing Members and Carrying Reputations

Students, given the high degree of pre-design socialisation have developed expectations of peers prior to design and, in some cases, was informed without any prior direct interaction or communication.

A lot of… I have to say; Dominic did a lot of the decisions in terms of material balances and assumptions. [Laughs] a lot because he is very highly numerate. He can't write to save himself, I had to write his whole material and energy section for him because it was just awful. - *Frank Hill*

And when you get into Barony Hall without knowing who your group is, you could get anything, you could get anyone in your group. Basically, it's a lottery… I was very scared. And even though my group was great working together, when they gave us the sheets out I looked through the names out of the six people I didn't know four of them whatsoever. I knew them… I've seen them… Like, two of them

I've never seen ever. Because they didn't, they never showed up to any of the classes ever. So, I already had this main fear of "oh no, they don't do work because they will not come to classes" and then the other two I was like "I don't know them well, but it's fine." - *Spencer Jennings*

Great. So, was that the first interaction with your team members I knew a few of them beforehand but only briefly from speaking and things like that. There was nobody I really knew well.

So, how was that interaction?

It was all right. You know that way where you know people, so you know that some people are like… You are kind of just a bit disappointed, because you don't have big grafters in your group. The people who are going to help you pull the weight, you kind of got the people who are like, "ah, we'll do it when we do it." I don't like that [laughs]. - *Aman Chowdhury*

I was happy with my group… Because I knew from the people, that there wasn't anyone, apart from Nicolas, maybe, but he has worked quite hard. But they all work hard and I knew that they would be willing to work hard. - *Iona Mitchell*

We had our groups, I was happy with my group – I knew everybody bar one member – and I felt that the group would have a good dynamic because I was quite friendly with most of the people. - *Phillip Easter*

I quite like my group. Because I had my flatmate, then I had a boy that I did an internship with last year, I had one of my other friends. And then there were two boys who I didn't really know. But I thought they seemed nice enough – that's the thing, everyone is like "who's in your group? Who's in your group?" But I quite liked my group, I've got quite a good group, especially in comparison to others. So I was feeling quite confident, I feel like they are quite a hard-working group. - *Natasha Douglas*

Some students emphasised the importance of being acquainted with design group members and how being "friendly" with individuals translated to expectations of positive group dynamics. Students compared groups and evaluated quality of the overall group according to the reputations of individual members, carrying several characterisations of their peers into the design project. Therefore there were 'good' groups, with high representation of students who worked hard and those considered to be technically adept, and 'bad' groups comprised of a high proportion of students for whom there was no social information and those who had reputations of 'free-riding'.

Frank Hill highlights how a group member, Dominic, made 'a lot of the decisions' relating to technical aspects but struggled with written components. This evidences how students with reputations of technical competence were afforded more authority over technical design decisions.

In the context of this research, there is a spectrum of familiarity among the student cohort. Students are often acquainted with peers, so seldom are completely unknown. Where such instances were reported, of a student being completely unknown, there was significant stress and concern about how contributing such individuals would be (Spencer).

5.7.2 "Gonna Kill Each Other": Maintaining Pre-design Relationships

An additional possibility arising from students pre-design socialisation was design groups being comprised of students who were friends. Two participants reported their experiences of working with friends who were assigned the same design group.

> Well, when we got our groups out. That was the first thing – everyone was like "oh," – because I was with my flatmate. So I was like "oh, that's so handy." But everyone was like "no, you're gonna kill each other." And I was like, "I don't think we are? We work quite well together." But I think that was the first thing, everyone was like "oh, this group is so good," and people complaining about their groups. I was like "it will be fine in the end. It will be okay." - *Natasha Douglas*

> Well, I feel like with my flatmate she was like, she always wanted to work with somebody but then you would end up just doing the work. I quite often worked with her, but I just end up doing it. But the thing is, it is hard when your group – because some of the work is basically for one person – like there's only so much you can do together, it is just quicker if somebody just does it. But then she wouldn't then go on and do something else. - *Natasha Douglas*

> Like positive relationships with all of them. The two guys that I was in my subgroup with, it's like - it's a really good friendship as well, which is - actually it's good and bad, because it's good because you can… It's more enjoyable doing the work, but it's bad because sometimes there are less productive times. - *Will Ross*

Both Natash and Will recognised the tension of extensive pre-design socialisation on the ability to work productively. Where Will emphasised the challenge associated with high familiarity/friendship with group members resulting in distractions when working on design, Natasha highlights the difficulty in confronting her flatmate to contribute when this was found to be lacking. In both instances the prior relationship offered a familiarity, which promoted group cohesion, however, this can override the formal work of the group. Natasha suggests that this high-degree of familiarity can make confrontation with a group member more difficult.

Most group members were unfamiliar with one another and, hence, the social ties are developed as part of the temporal nature of design. Such relationships were brought about through the shared experience of design. Where a prior relationship existed, such students must introduce the design and its associated activity into the existing relationship. Since such relationships will outlast the design project itself, professionalism becomes challenging to implement. There is a tacit understanding of this demonstrated by Natasha's peers and their cautioning her about working alongside a flatmate in her group, who understand the inherent tension of working with someone you are well-acquainted with.

5.7.3 "We Went Out": Socialising beyond Design

Some participants highlighted how the design experience, especially around the initial phases, involved socialising with groups members beyond the design itself.

> No, that's the thing we all get on great – that's the thing, we all enjoy our company. And, yeah, we get on – we went out for dinner with each other after the presentation. - *Frank Hill*

> Yeah, we used to… Sort of halfway through we started having lunch together and stuff. Because at first everyone was just sort of doing their own thing, then we went out for pub lunches a couple times and… Lunches in the library, so… - *Billy Reynolds*

> Yeah. I think I definitely had the best group in the whole year. People kept on saying that ours – that we had the best group in the whole year. Like, so, last year the project was split up into three parts. After every part we went out to celebrate as a group. Like, we used to see each other every day but still we wanted to go out and celebrate together, it just tells you we were amazingly working together. Everyone did what they wanted to do and everyone got their stuff done as well. And I think everyone just had a good time. - *Spencer Jennings*

> So we went out… When we went out for our trip to Tenants, we went out at the very, very beginning as in week one. So, that was a good start, we went out for a couple of drinks and we went out for dinner a few times or we would like when we were, when we were actually doing the work we would like grab lunch or like, you know what I mean? We would take time out and between just to speak about something else then just… - *Sarah French*

Activities, such as dinners and lunch, were opportunities some groups took that appear to strengthen relationships with group members. These ranged from casual regular lunches to semi-formal post-submission celebrations. In addition, some groups took the initiative to arrange a trip to a nearby brewery. While it was difficult to ascertain whether such extra-curricular socialisation resulted in, or were borne out of, the positive group dynamics, there does appear to be an association. All of the participants who indicated that they socialised with their groups beyond the design project, also viewed their group in a positive light suggesting that there was a relationship between these two factors.

5.7.4 Splitting it Up: Compartmentalising and Distributing Collaboration

At the early stages of the design project, many groups recognise that the scope of the design projects necessitates division of labour. This was often reported matter-of-factly, indicating this is normative behaviour. This is further strengthened by discussion at the onset of design during the induction event with “division of labour” explicitly mentioned under a slide related to “Group Work and Communication”. The approach employed for “splitting” the labour varied between groups, as reported by participants.

> I think the first time round we divided up the work and we didn’t get that high a mark because our feedback was that it doesn’t look like it had been sort of done as a group. - *Billy Reynolds*

> But we were always giving each other help when – as much as you can – because when you focus on one bit, you don’t really know much about somebody else’s bit. - *Ellis Donaldson*

> Yeah. I was lucky that we split into, we split into sort of subgroups for the first phase nearby with three of us taking the energy material balances and the PFD. And I was for that I was working with a couple guys I get on really well with, and we sort of knew what we were doing and working hard but having fun at the same time. So that’s been good. It’s just been like, it’s not been - everyone’s doing the same thing. So it’s not like - you feed off everyone’s ideas. Yeah, its not been scary, not too bad. - *Will Ross*

> So, we split up the sections of who is doing what. We split it up into small groups as well. That was something I learnt from third year, because we had one person who – I won’t name names – who didn’t really turn up and help. So, we stuck him in a group of three and then everyone else was in a group of two. So, that way when he didn’t turn up it didn’t matter. You just did the work that way…. - *Aman Chowdhury*

> And that just helps, because you have a list you can look at and you can – maybe you’ve finished stuff early and you can go back and see if someone else needs some help on something else or you can do something else, get stuff done that isn’t. - *Cain Bruce*

> But with our group it was like, you know, anything that came up and it was just like, “I have a big decision to make and I’m not really sure - guys, can you help me out?” And then they would work in a pair and try and hash it out - couldn’t do that. we’d

> spread it wider. And so, then like, we divided up our areas. So, there were some areas that required actual calculation. So, your mass balances and the energy balances. There was like a couple people doing that, they were never left to do it alone. So, they always had someone to validate. - *Ewan Murray*

From the excerpts it can be observed that approach taken by students to "divide labour" varied across groups. Some groups, such as Billy's, initially opted for assigning single individuals with specific tasks only; however, there was a tendency for groups who employed this approach to lack awareness of the activities and outputs of other group members. This siloed approach to distribution possibly contributed to instances of social-loafing and free-riding; discussed later.

Certain groups explicitly divided the workload across "sub-groups". By ensuring that multiple group members were assigned the same task, groups ensured that there existed an internal mechanism for feedback and also increased the number of responsible individuals, thus increasing the possibility of assigned tasks being completed. Other groups, owing to their regular contact by working in close proximity, were able to divide labour individually and also ensure progress of assigned tasks. Furthermore, groups such as Ewan Murray's developed reactive approaches to forming sub-groups based on challenges presented to the wider group.

5.7.5 "Bouncing off ideas": Feedback and Perspectives

One of the most frequently reported group functions that were valued by participants was the opportunity to 'bounce ideas' off group members. This was linked to, and enabled by, students sharing physical spaces to work with group members.

> Yeah. Like how to tackle stuff. And if someone had a difficulty with their section, they'd sort of raise it… Just like I feel that we had a mixture of skills and I feel that… Because, say for instance I would say that Mia is the best in the year. So she was really good at research and technical stuff. And then Spencer was like a really strong researcher as well, he would spend hours and hours and hours and not get bored. He would sort of keep crashing through… And then I'm not quite so passionate on the engineering but felt I was really good at the report writing as well because I proofread it - *Billy Reynolds*

> But then as a group, I mean, you know, I can always bounce off someone and say, you know, "how you getting on with that bit? Do you need any help?" And they can do likewise with you. So, I mean, that was always good. - *Ewan Murray*

> And meetings a couple times a week, you could build everything up. I think for phase 1 we basically all just sat together most of the time. So, you could just ask each other questions, bounce ideas… - *Aman Chowdhury*

> Positives… Good teamwork; new friends; their ways to look at things; a serious benefit from other people's ideas and experiences with chem eng because, like the way, I view it is different from the way other people view so it's been phenomenal having other people who are better at working at reports thinking, "This! This goes well", which I'm not particularly good at and then when we had to cut words down and stuff yeah I'm not good at that either. But these guys were really good at making those decisions and the guys who did like the eco- economics, environment, locations, stuff like that, absolute nailed their parts as well and these are those things I wouldn't be so great at. And so yeah, serious benefit from mixed ability though from different abilities they're… - *Will Ross*

> Myself and Lauren sat down and read about the packing material – we had this big textbook that I had and it had advantages of looking at packed bed over stirred tank. Looking at all that, and then we made a decision between ourselves but then we actively said "when we go tomorrow, don't let them know what way we stand on it, just give them the lists and see what they make of it". And that led to quite a healthy conversation of like – because they went the other way, they made the wrong decision [laughs]. But, I mean, they allowed us to argue the case a bit more and make sure they were – it made sure that everyone on the team was on board with every single aspect of the decision. Rather than "we've chosen to do that, so that's what we are doing". - *Cain Bruce*

> Yes, so like, we would all like write down what we found. So like, remember I said we all took a separate section? We didn't write it up definitively, it was just sort of like short sentences, just like "this is what I found, this is what I think I should put in it" and then we got feedback from everyone else. - *Sarah French*

'Bouncing off ideas' was an approach taken by students to gain alternative perspectives on tentative design decisions and findings. To improve the quality of solutions and develop confidence in their work students developed organic feedback loops through their group. Since students' individual design tasks were often interrelated with group members, there was a shared conceptual space that enabled these feedback interactions.

Furthermore, the first phase of design demanded shared ownership, strengthened through the language employed in the brief and assessment documentation, further promoting such interactions. For students, these interactions offer a social and non-assessed (or formal, vis-à-vis supervisory feedback) approach to reduce ambiguity in their design decision making. There is an understanding that different perspectives are key - some students may be unable to fully contextualise a component of the design given their ignorance of other members' components. This process of bouncing off ideas, then, offered an approach to contextualise individual allocations of design with the wider design decisions of the group.

5.7.6 "Sitting Together": Sharing Physical Workspaces

The established norms for a group with respect to how they physical located themselves (i.e. the frequency and degree of co-location) for design work was a surprising factor influencing student behaviour and beliefs significantly during design. Certain areas, such as the computer laboratory located on the same floor as the chemical and process engineering department's offices, were areas where significant numbers of students undertaking design congregated. Preferences of working in shared physical spaces for the majority of the group phases in their assigned groups were reported by multiple participants.

> It was quite natural… For phase 1, five of us would always sit together and work together for everything – so that helped a lot. Emelia does ACCE so she had her other classes, so she would sometimes sit with us. But she doesn't like the James Weir environment. But five of us would sit together and work. Not all groups did that. - *Iona Mitchell*

> Communication was never the problem, we were always very kind of talking together, we worked together everyday in the same room which was great. We were always kind of asking each other "is this okay, is that okay?" - *Frank Hill*

> You normally have a meeting spot. You come in and there will be somebody working already. It's like a job, the office chat like, "how are you feeling about this?" You can roll back your desk chair and be like, "what do you think about this? Is this looking okay?" It's that constant communication. - *Cain Bruce*

> In the first one, we very much worked as a team, we sat together and did it all. Even though we were doing our own individual bits, it was very collaborative. We spent most of our time doing it together. - *Laura Dawson*

> Well there was a room that we used to meet in, in the library on the fifth floor, this sort of group discussion room really, so that's… Because every day we had the same table because Spencer and Mia were quite early risers so they just used to come in and do their own stuff and they would like grab the table at eight. And when the rest of us got there at like 10 they were already there. - *Billy Reynolds*

> So, at the start we were all about – I can't really remember… So – I would say phase 1 was probably more difficult than phase 2 because we all thought we had to work really closely together because it was a group mark. So, I think people were wanting to – though the vast majority – were wanting to put a lot of effort in for the group. So, I think after that – after phase 1 – we were all a lot more comfortable talking to each other and working together. - *Sophia Duncan*

> And then it was more of "how often do we want to meet for as a group, as a whole, just to feedback to everybody various progress." And we decided that probably two days a week, we would just meet up and try to work together. The majority of the day. Not like – we would all focus on our individual tasks, but it was sort of like everybody is there if discussion is required. - *Phillip Easter*

> We met like three or four times per week in University for like hours, because we decided to work together. So, we had this area in the library, but we kept using for the three months and we used to work together, so they used to come every single day, so there were no complaints. - *Spencer Jennings*

Many students reported congregating with their group in physical sites for design work. Some of these were arranged by programme co-ordinators to facilitate access to computer facilities for students participating in design. Groups of students also arranged sites for congregation informally, at various alternative computing laboratories or library areas too. From the abundance of reports, group members working together in physical spaces appeared to be the default approach to coordination of design conduct.

There were reports that some group members, like Emelia from Iona's group, opted to work in a different physical space from the rest of her group. Other commitments are mentioned, and this was verified with Emelia herself.

> **Was there any other kind of challenges relating to the group design project itself in terms of…**
> I guess, sometimes just - Yeah, I'm guess… it is like, I feel like I'm not exactly the - on the same level as my group.
> **In what's sense?**
> Like, well, I'm guessing it is because they had so much time together. But I don't know they've just - they're together a bit more as a group. - *Emelia Emese*

Emelia belonged to the Applied Chemistry and Chemical Engineering (ACCE) cohort, a minority group which took fewer chemical engineering classes, and this was potentially a factor itself which may have led to barriers in her fully connecting with her group. She acknowledged the importance of the group being "together" influencing their overall cohesiveness, which is somewhat expected. Where there exists group cohesiveness facilitated by working in shared sites, comparisons of activity are made by group members.

> But yeah, comparing yourself with other people is never the right thing to do. But I did feel like when I was seeing the other guys in James Weir doing stuff, when I wasn't making progress myself, I was like "you need to start doing stuff". - *Will Ross*

When comparing with peers, students make judgements about their own and group members' activity. This allows students to qualitatively evaluate relative effort and progress. This process of comparing with members, then, allows students to obtain feedback on whether corrective action needs to take place if the difference in relative activity is deemed too great. Will demonstrated a case of positioning himself with "negative relative activity" and hence, was motivated to correct this by attempting to lessen this gap through an increase of his own activity to mimic that of peers. There were also reports of instances where students assess themselves with a "positive activity" difference with peers, discussed later in section 5.7.9.

5.7.7 "The Zoo": Sites of Comparison

Physical sites which facilitated colocation were helpful to allow students to work closely with group members. These allowed ease for ease of communication and information exchange, however, this was not limited to in-group communication. Students also reported the cross-pollination of ideas and information exchange across groups. These sites could also, counterproductively, lead to excessive interaction between students which in turn could inhibit design progress and introduce doubt into decisions.

> Everyone has so much chat, because everyone is in James Weir doing different things, hearing different things and then it just leads to so much confusion and self-doubt [laughs]. - *Sophia Duncan*

> That's what we called James Weir, we called it "The zoo". That's what it was called… Because as soon as you walked in, it was just so noisy and busy and people coming to check on you, so we just called it the zoo. So, that's why Livingston Tower was a lot more chilled, that's where you went if you… You could work and you could speak to people, but people were a lot more calm. - *Natasha Douglas*

Some groups opted to locate themselves in less populated areas as a result of excessive comparisons, such as Natasha Douglas' group. This evidenced an attempt to constrain the environmental conditions to allow for a beneficial level of comparison to take place; excessive comparison becomes counter-productive for student progress with designs. Even so, some students, owing to their conviction in their developed understanding, were able to resist peers' challenges, as demonstrated by Cain Bruce below.

> At the start of phase 1, there is this patent that has the first phase being continuous and the rest being batch – and our group looked at that and went "that looks silly, let's not do that, let's just do it all batch because that first part will be dictated by the rest of it. So, would be continuous equipment running in batch mode which is going to be expensive for no reason," but then the next day we would go into James Weir and people were like "aw, are you doing the continuous first?" – Like every group doing a continuous first bit – like, I think three different people asked me if I was doing that and I always said, "why are you doing that?" – "Oh, the patent said it." –

> I was like, "the patent said it and that groups doing it…", I was like, "no…" That's when I started saying to people "why you doing that? Why do you think that's…?" Mainly because I wanted to validate my own decision, if they had found something, then [laughs]. If they had said that would be a good way to do it, I'd want to know about it, but also just to make sure they had their rationale right, like "why you doing that? Are you sure? Does that make sense?" And I think most people went to all batch mode, but… - *Cain Bruce*

These interactions demonstrate how students actively sought to verify their decisions through questioning and challenging one another. Cain mentions "three different people" approaching him, which evidenced the normative nature of approaching peers and requesting verification of their approaches that was carried into design from students' previous experiences on the wider programme. This was also supported by Natasha Douglas' comments related to being "checked on". Interestingly, Cain suggests that eventually, most groups came to a similar decision with regard to this particular technical design decision. Critically, this strong justification opposed both extant text in the form of a patent and the wider acceptance from other groups. This suggests that such contrarian positions, if held with sufficient conviction and supporting justification, can overwhelm dominant views held by the cohort. Such instances demonstrate the influence of "creative minorities" on "conformed majorities".

5.7.8 "Working Harder than Me": Comparing Effort and Reducing Differences

By working in close proximity with one another, students were able to judge their own effort relative to their peers.

> Also, when we were working as a team to put it together, you're really seeing how different people like worked in those environments. There are some people in my group, brilliant, really good workers, but they will do work until like two in the morning in uni. And I'm like, "Nah, I don't want to do that." I'll be like… I think I stayed in till like half ten one night and I was like, "Nah, I'm done, I can't see how you guys can work through like that." And then, like, the commitment everyone showed was like, really, really positive and you just felt like, I just wanted to be there. I was like, I couldn't stand if they were, all in at like nine. And then I was coming in at like, 10 and then they'd have all discussed things and then having to catch me up on stuff. And which, which was really good. I enjoyed that aspect of it. - *Ewan Murray*

> And there are some people who have been working really hard throughout their degree, continue to work really hard on the design project. I feel like that was one of the things that actually motivated me was seeing people who were working harder than me. I was like "Ah sh… I really should be doing something right now."

> So, then that would push me on as well. Also, contributed to my feeling of inferiority, though, because when I was doing stuff to catch up with where they were, they were taking steps forwards too. But if I hadn't seen them taking those steps forward, then I wouldn't have kicked myself into gear. - *Will Ross*

> Because sometimes, even in the library, sometimes, I'd get up and go get water, and I'd be like "no, I can't go and get up and get water because I've not done anything" is just like procrastinating. But then I think I would, if I didn't have the pressure. - *Billy Reynolds*

Some students reported a sense of guilt associated with a lack of demonstration of their effort and productivity to group members. When observing group members working there was a positive feedback loop, through which students cycled through different social evaluations. Students were effectively engaging in iteratively asking the following questions:

- What and how much are others doing? (peer-evaluation)
- What and how much am I doing? (self-evaluation)
- What, if any, difference is there from my peers' and my activity? (comparing for differences)
- Change behaviour to mitigate difference. (mitigating differences)

Where differences were observed, some participants suggested that there was a feeling of shame which motivated action and change in behaviour. The degree to which students' behaviours aligned with their group related to the perceived strength of group membership. Effort and productivity, then, are evaluated relative to peers and group members. This could lead to behaviours which appear to be excessive demonstration of effort, as reported by Ewan Murray. Another aspect alluded to by Ewan, was the possibility of missing critical discussions. Emelia, discussed earlier, suggested that her commitments to chemistry classes hindered her ability to connect with her group and there was a general sense of being an *outsider* as result.

5.7.9 "Going to Get Ruined": Free-riding

Where some students observed a significantly "positive activity" difference between themselves and a peer, it was assumed that such a peer was *free-riding*. Where free-riding was disclosed by interviewees, it was also reported that peer-review was among the favourable means to lessen the relative activity gap.

> But as a group there was one member of the group, Adam, he is very capable but he's very lazy. So, there were times where we felt he didn't contribute enough to the group but that reflected in his peer review. - *Sarah French*

> Everyone had done a fair bit of work and then James – this was after about ten days – "James, what's the industrial price of ibuprofen?", "Oh, I couldn't find anything much about the industrial price of ibuprofen, but I know that liquid capsules sell for six times more than powdered capsules." That was literally it. And then it

moved on to the next person. And I was like “what the fuck?” And then another week later he had still done nothing …his work is just shocking. I was hoping there was going to be peer-assessment for this project – there was meant to be, but they pulled it. I don’t know why, there was meant to be a peer-assessment. And me, and well, the whole team basically they all felt the same as me. We literally agreed that he was going to get ruined, like we were going to give him 1s for everything. - *Cameron Hooper*

When we handed in phase 1 – it was due on the Friday, on the Thursday he came up to me and he was like “Ah, are we meeting tomorrow again?” And I was like “oh yeah, I’ll probably meet at the usual – 10” and he was like “oh, because I’m going to Glencoe…” And we were just like, “what?” He was like “I won’t be here.” And I was like “oh… Why?” And he was like “I’m going to Glencoe” and I was just like… And at that point we thought we had to submit it individually… And I was like “oh, you’ve got to submit it.” And he was like “oh, I’ll take my laptop then.” And I was like “you might not even get reception” and I was just like “oh all right, okay…” And then the boys [group members] were like, “What?” They were like “he’s going to Glencoe?” And I was like “yeah,” and they were like “that’s ridiculous!” So angr- And then we obviously, had to rewrite – that was the boy we had to rewrite all his bits on the last day. So obviously, they were so angry. - *Natasha Douglas*

Yeah, there was a point where – was it the second phase? I can’t remember, one of the phases. But somebody had been doing the market research and his part had been basically copied off the internet. And we were looking at it and scanning through the report like, “this looks awfully familiar. I think we’ve seen this on a website before.” So, we had a bit of a confrontation to approach him and be like, “where did this come from?” And initially he was like, “no, that’s definitely mines.” And we were like, “it’s definitely not your work. We’ve seen that before.” - *Laura Dawson*

At the start – I don’t know if that it was maybe the time of year, but because a lot of people were looking for internships and stuff – you had a lot on with the timeframe of phase 1. Because that was really tight, a lot of stuff to get done. We had a guy in our group who was just spending so much time doing applications and all sorts. And we had given him a pretty small section to do and he had from Monday till Friday and then he came back on the Friday with three bullet points and that was supposed to be the introduction and… it was difficult. We already had enough work to do, you don’t want to say, “oh, it’s fine, we’ll do it” because he’s not bothered and we thought that we could do it better, you need to actually let other people do their work. So, I thought that was quite challenging… - *Sophia Duncan*

> There was one group where the girl was like, to me, “this boy, there’s not one word of his in their phase 1. But they got 72% – he gets 72% for literally doing nothing, for just showing up and putting his name on it.” So I do get that as well – and that starts causing – I feel like people are quite bad – nobody says anything to anybody’s face. They just come to you and just come and complain like, “oh, this person they are awful, they don’t do any work.” - *Natasha Douglas*

Sarah French highlights her experience with Adam’s delayed communication of his design outputs which Sarah required for her own design. Cameron Hooper expresses his frustration with James’ contributions after significant breaks in contact. In both instances it was suggested that the free-riding member did not opt to share a physical space with group members for significant periods of time. Both Sarah and Cameron declared that peer-review was the mechanism that they ultimately relied on to simultaneously penalise and communicate their frustrations with the free-riders. Natasha Douglas also highlights instances of free-riding and the associated tension this gave rise to with the rest of the group, but also implied a tendency for not directly addressing free-riding. We find that either perceived low quantity or low quality of contribution was common to all reports from participants with regard to free-riders. However, these aspects were not the only factors contributing to the group’s views towards such students, suggested by the following comment from Sarah French, who attempted to appeal to Adam.

> I tried to, I tried to say “come on Adam, this is a group project you need to…” Like, there was times where we were submitting the first part, he never showed up for the submission. You know I mean? I think his attitude was “aw, it’s finished,” but what he didn’t realise was that we were still formatting it that day. - *Sarah French*

The notion of *member presence* influences how the group views free-riders and other participants such as Will Ross and Natasha Douglas reinforced the significance of member presence with respect to their experiences of present but otherwise ‘free-riding’ students in their respective groups.

> And even though there was 6 of us and four us did a lot more than the other 2 but I dunno I feel like that was sort of affected by… I dunno if I mean ability or work ethic or just whatever. It wasn’t a problem. We were all happy to do it, the other guys didn’t do nothing, they did do stuff. They did like, I dunno, kind of what you’d expect from them. And so, yeah I think everyone worked to the expectations that we had and that was fine. We had the HAZOP, the four of us who worked our arses off on it and… but the thing is, they always showed up. So, when we were doing the HAZOP in the three days before the interview, they showed up and they sat through like 10 hours of being at a computer with three other guys because we were doing it in shifts. They didn’t say anything, didn’t contribute very much at all

> but they were there. Some people would be like "if they're not gonna say anything then they might as well not be there". And that is true, they might as well not be there but the fact that they are there means you don't hold resentment. Or the fact they are away doing their individual thing and you're just slaving away on their behalf, they put themselves there. And they didn't do anything, and it was annoying because we would have got through it quicker if they had contributed but the fact that they were there it meant that I didn't harbour any resentment towards them, even though they didn't contribute. - *Will Ross*

> And there was another boy in our group, well, there were two others and they were a bit like that as well, they would do the group work, but then like not – they would be present, but they wouldn't really do anything. But they would try to do the extra stuff like "oh, maybe I should just do this instead?" And tell you were like "oh, why don't you go and try to do this." But the other two boys were quite good, they were quite on it. - *Natasha Douglas*

We observe from these excerpt that *member presence* plays a crucial and nuanced role in deterring feelings of resentment from group members, like those experienced by Cameron Hooper and Natasha Douglas's group, which is accompanied with free-riding. Physical presence from a group member demonstrated a commitment to the group but required a group which normalised working in physical proximity with one another. While both excerpts, from Will and Natasha, demonstrate that there was some discontent with the efforts of the members in question, both distinguish the idea of presence and effort. While these students demonstrated relatively low effort, they remained present throughout the group phase and therefore this compensated for the reported lack in their contribution. On the other hand, Natasha's original report of the member who was absent at the critical time of the phase one submission, reveals that there were times at which the significance of member presence (or absence) was exasperated.

5.8 "Individual" Design Practices

It was observed that the students' salient social processes differ somewhat to those concerns in the group phases of the CE design. This involved a much more concerted effort around overcoming doubts on their designs and students constrained their practices based on the context of individual design, in the academic setting.

5.8.1 "Splitting Up": Disintegrating Original Groups

Once students entered the individual phase of design, made explicit by a shift in assessment from group to individual, many group members respond accordingly by partly or, in most cases, significantly reducing group interaction. This disintegration of the group then prevails for most of the duration of the individual phase of design.

> **How's the group interaction been in phase 2. Compared to phase 1?**
> Low… Really low. Just because, as I say, everyone kind of goes off into their twos or threes with other people, not your group, because… There's no point, for me. Apart from just to say how you're getting on to submit your minutes, there is no real interaction. So, I'm sure phase 3 will be better again. - *Frank Hill*

> Everyone basically split up to be with their friends who were doing similar things. Because it's easier to work when you are all focused on the same thing. So, even if you are in the same room, it would be a larger group you were sitting in – so, I'd be sitting with two of my friends who were also doing the evaporators. Other people would be sitting with the people who were doing something else. So, we split up like that. - *Aman Chowdhury*

> I don't really know if there was much of a group dynamic for phase 2 because we were all doing our individual part. The only time we met up was at the very end and we did all look over each other's just to see because at the end we had to compile everybody's work. - *Sarah French*

> Between the phases themselves… I mean, the isolation of phase 2 is a big aspect because it is individually graded. There is a small contribution from the group, but you do your section on your own, so this is a very different day-to-day lifestyle. - *Cain Bruce*

> So, our group didn't sit together anymore in phase 2. I started - for the first few days I worked by myself because I just didn't know who else was doing the crystalliser. - *Natasha Douglas*

There was some indication from participants that the language and implementation of assessment used in the academic context of design (e.g. "group" and "individual") may have a significant impact on student behaviour towards their assigned groups. The responsibility of assessment influencing group communication and interaction between members of assigned groups.

In most reports about the transition from "group" to "individual" phases there was an indication that some degree of disintegration of assigned group took place as there was limited mutual incentive to remain as a group. Students no longer shared the same design requirements or occupied the same design problem space. The initial student response to individual detailed design is to disintegrate with their groups in order to orientate to their own individual design tasks. At the onset of phase 2, the processes of "splitting up" with the group and "sitting with friends" are considered normative in the excerpt from Aman. Although, not all participants shared the component of friends in this process, two key processes emerge: disintegration of the assigned group and collaboration with comparable peers. This is other evidence to suggest that the original group loses the motivation for group-cohesiveness due to the academic context. Similarly, through the awareness of the academic context, students collaborate with friends and acquaintances.

5.8.2 "Purposeful Picking": Maximising Accessibility of Shared Conceptual Space

Prior to starting the detailed design phase, students must negotiate their allocated unit operation. Some students reported that they had pre-arranged to select certain units for detailed design based on discussions and agreements with friends who were based in other groups.

> **Okay, cool, that's cool. Were there any other decisions like what about - I mean, there tends to be is the splitting up of, you know, unit operations tends to be another kind of big decision fork.**
> Yeah, nobody wants to do Friedel-Crafts because the impression was that there was no data available for kinetics for that. And Tyler and I ended up doing it. The way we decided to do this was - there's another guy who Tyler and Louie are really good friends with who was like, high-flyer, top of the year, and was also going for Friedel-Crafts and so I said, in the first meeting we had together when nobody wants to do it, I said one of those two should definitely do it because this guy is… he's, he's gonna surpass expectations early on, and he'll be able to talk about it with you. I'm happy to do it. I'm happy to be on Friedel-Crafts as well with you, but one of you two needs to be doing as well so that we can work with him. Okay, and so this is… - *Will Ross*

> **So, you mentioned that the group disperses and start working with people doing similar sections. Could you tell me more about that? What was that like?**
> Well, that was almost like – it was a different dynamic because you could… Because some of my friends purposefully picked the same one within our group so we'd knew we could help each other out. - *Laura Dawson*

> **So, how did you figure out who was going to be doing what?**
> Just discussing would actually done the initial research into each of the sections. So, I'd done research into the evaporators. I'd done all the mass and energy balances, so I kind of knew already how they would work which was why I was quite interested in doing it. And part of it was also because I knew two of my friends [in other groups] were also going for it. - *Aman Chowdhury*

These reports demonstrated a significant effort from some students to strategically position themselves for the individual detailed design. There is an active approach described above which was taken to ensure that individual technical tasks were assigned so that these were comparable to those assigned to friends. By aligning themselves with friends, such students are able to maximise the conditions for collaboration to occur. Friendship was not a necessary requirement for collaboration but a facilitating factor as alluded to by Natasha Douglas below.

> And then it turned out my friend was doing it, so we had the crystallisation crew. So there was three or four of us. One boy was there in the beginning but then he just stopped coming in and I think he felt a bit guilty so he just stopped coming to the group. - *Natasha Douglas*

Such instances, as outlined in these excerpts, highlight that students are not only subject to the constraints of the design project emerging from the educational setting, but demonstrate that students are active agents in constraining the educational setting. By engaging with friends and peers students are displaying a nuanced awareness and subsequent influence of the academic context through co-ordination with other students. Students behaviours suggest that although there are constraints placed on them by the design project as an academic exercise, it is not divorced from their prior experiences with friends (and peers, supervisors, academic staff etc.). All of these pre-acquainted design actors contribute to their understanding of, and behaviours in, the design project.

5.8.3 “Moral Support”: Socialising with Similarly Tasked Peers

The process of collaborating with comparable peers serves an essential social support function as well as the pragmatic function of addressing the design task itself. The personnel in the group or team not only offer the possibility of receiving mutual, sought-after resource, as evidenced by the frequent distribution of labour, but also offer social and emotional support throughout the task.

> It’s more lonely… I’m in a room on my own eating lunch away. Sometimes I’ll meet people who are from different groups who are doing something similar, we’ll have lunch and stuff together and talk about the ability to… It’s a different dynamic, absolutely. - *Cain Bruce*

> So, I think it was a lot easier to work in. It was a bit more chilled because it was kind of just nice to have the company. - *Natasha Douglas*

> And I think that’s why. I think a lot of people – again, it comes down to the moral support. You know? You’ve got your pal there, you can kind of, when it’s shit, you’re both finding it shit together – a lot of that kind of stuff. So, I think that’s why a lot of people just go together. - *Frank Hill*

Students transition from their assigned group tasks to an individual task and this can, and in many cases does, lead to a disassembling of the social connections with the original group. In the process of moving to an individual task, students lose the condition which holds the original group together – the shared goal which is supported by shared assessment. In the place of a shared goal, is an individual goal. The similarity of student goals act as sufficient justification for inter-group communication and, as individual members begin to detach themselves from the assigned group, other members are prompted to seek comparably-tasked peers to replace the social support, further dissolving the group.

This demonstrates that a key condition for peer communication, collaboration and support in the design task is the presence of a shared goal. In the absence of a shared goal, as is the case for detailed design, a sufficiently comparable goal is often necessary for continued group cohesion.

5.8.4 "Quasi-Groups": Sharing Conceptual Design Space

The phenomenon of students collaborating with comparable peers was reported by several participants to be a normative behaviour among the wider cohort.

> The only reason we found out was because I found out from other groups. Obviously, because everyone works together. "Oh, you're doing the stage one reactor?", "you're doing the stage one reactor?" and then you've got five different students from different groups, and you're all sitting round the computer together but you're all doing the stage one reactors. - *Cameron Hooper*

> Everyone basically split up to be with their friends who were doing similar things. Because it's easier to work when you are all focused on the same thing. So, even if you are in the same room, it would be a larger group you were sitting in – so, I'd be sitting with two of my friends who were also doing the evaporators. Other people would be sitting with the people who were doing something else. So, we split up like that. - *Aman Chowdhury*

> Well, working with my friend [Louis], whose doing the purification step as well. I think we are very much working together through it. Because obviously we don't have the same supervisor, so we are going to work together – obviously not doing word for word the same report, because you've got different flow rates and capacities and what not – but, that's definitely helping, having somebody else to work through it with. - *Frank Hill*

Students communicate with other students outside of their assigned group frequently even during the group phases, exemplified by Nataha Douglas's "zoo" comment (section 5.7.7). Students share and receive information about the design aspects for which they are responsible. From this exchange of information to and from the wider cohort, students are able to identify the individuals who are assigned a comparable task.

> I don't think you can really compare it because the work you do is so different in each of them, but it was good. At that point you formed a different group, so, you are in your design group for the first part but then we all kind of split up. And I knew other people that were designing the same unit as me, so, you kind of went to a different group. Because, we'd all talk and be like, "I'm doing this, I found the source." Which was – but that was all dependent on who else is doing… - *Sophia Duncan*

With this information, students identify pools of individuals who can provide assistance as they complete detailed individual designs. Students compare tasks to identify areas of difference and similarity between their own task and that of their peers. These differences frame the degree of assistance students can expect to obtain from their peers; the greater the similarity of initial task constraints the greater assistance that can be sought from peers. The critical component of this collaborative approach is the commonality of designated design task. Another way to frame this is the idea of a "shared conceptual space" in relation to the design task and goal. Students are able to collaborate when they share a significant conceptual space for design tasks. It can then be posited that when there is little overlap of conceptual space, direct collaboration is less likely to occur.

> So I was doing a different – they were all doing distillation columns in stage 1 and I was doing in the second stage. So, I wasn't dealing with the same thing as them, but Simon was doing things after me – so was easier to ask him questions rather than ask them questions. - *Iona Mitchell*

We observe from Iona Mitchell's comment that there were instances where the conceptual space can be shared even without complete task resemblance. Here we find that original group members with 'adjacent' design tasks had enough similarity in design requirements to justify collaboration. In contrast, Cain Bruce, evidences the struggles in maintaining communication with the original assigned group.

> I certainly feel less inclined to ask my group for help on Facebook and stuff, because they have their own problems. And I asked them about my XS thing today because I was just not sure that the decision we had made… I was like "sorry guys, but I just can't…" I think the fact that I felt the need to say sorry at the start of that message is just quite enlightening. - *Cain Bruce*

Cain emphasises how students have "their own problems", which demonstrates that without a shared conceptual space or responsibility, collaboration becomes more difficult. Often students engage in collaboration because it offers mutual benefits to collaborators. Students, it appears, do not behave in an idealistic altruism but are governed by a principle of reciprocity when engaging with others.

Not all students' tasks are significantly comparable to others' and therefore opportunities for collaboration are impacted.

> If it had fallen that I was able to work with other people, then I probably would have done the same thing. Everyone's going to do that, but I didn't even think about it. People weren't working together on the bit that I was doing. Not every group designed the bit that I was doing, there was only 16 groups, so… Yeah, I know of two or three other people who were doing the same bit as me. - *Will Ross*

> Well, because see for phase 2 especially… I know that I was the only person that done a heat exchanger network in the whole year. - *Sarah French*

Even students who reported not working with similarly-tasked peers recognised that if available and accessible, they would have opted to formally collaborate with such students. Sarah French had an awareness that she lacked a shared conceptual space with any other peer in her cohort - such knowledge would have likely been obtained from the knowledge sharing that is characteristic of the wider sociable collective. Will Ross also realised that due to earlier design decisions in the group phase, this lead to a restricted conceptual space for the individual design where the pool of similarly-tasked peers was significantly smaller. Again, there was an awareness that those that did share the same space had not coalesced into a shared group. It can therefore be stipulated that accessibility of comparable peers is a condition for collaboration to occur, however, even where accessibility was difficult for students, collaboration could still occur.

5.8.5 "They Could Help": Collaboration Continuum

Many students arranged themselves in collaborative groups of similarly-tasked peers, however, multiple clusters of collaborative groups existed. There would still however, exist some communication between clusters of student groups, although the extent of collaboration could differ.

> And it was sort of good to know people that were doing distillation, because if you had any problems; no doubt they could either help you or tell you where to go or they were stuck themselves and it was like, "right, why don't we meet up and sort of clash head on this- try and overcome it." - *Phillip Easter*

> That's the exception. Say, you say "how did you get your agitator speed?" And someone will say, "in Coulson and Richardson". Or, "I've heard that in Coulson and Richardson, go to section three, page blah. it's not really on the graph, but I extrapolated down to get this value." You know, your two type of answers, the guy

> that doesn't want to tell you and the guy that just goes, "I sat and found it, and I'm sure someone will help me, so I'll help you." - *Cameron Hooper*

Comparable peers functioned as primarily a source of assistance in times of difficulty. A common form of this assistance was as a guide who may be able to direct individuals towards information that would be useful in "overcoming" the challenge. Assistance could also take the form of working together in a shared physical space. This represents a "continuum of collaboration" given one student's relative progress to their peer. There is merely "pointing in the correct direction", when there exists positive relative progress, to "seeking direction", when there exists negative relative progress. Within this continuum there exists the informal agreement for reciprocal co-collaboration. This describes the phenomena where students regularly interact in self-organised groups where members "brave the road together".

5.8.6 "In the Same Boat": Grouping Efficacy

Multiple students reported a lack of self-efficacy when presented with the idea of tackling the design individually.

> So I don't really know if I did it completely by myself, how far I would have gotten. I don't know, it's meant to be individual but I feel like you need other people. When it's something you don't really know much about – it would be just so easy to get this idea in your head and think it works. And then you're completely wrong because nobody has really challenged you. So, I think that was quite good. - *Natasha Douglas*

> And it's probably not allowed, really but if you are – if you didn't do it you might have gotten nowhere. - *Phillip Easter*

> Because, right now, if I was doing it myself, I would just be in no man's land. I wouldn't know where to go. And at the moment, progress is slow, but we are making progress, we're getting somewhere. - *Frank Hill*

> I think, its just easier. Because it's just such a hard thing to do. Like, design a crystalliser – and we've never been taught that in our lives before, there's nothing much really online, it's so much better having someone – two brains are better than one. And two people looking, researching is better than one. - *Frank Hill*

Interestingly, we observe students adopting behaviours to develop high group-efficacy in light of low self-efficacy early on in their individual design work. A high priority for students is to develop confidence in their tentative solutions. Collaborating with comparable peers is one such way for students to obtain feedback in order to build such confidence. Students in many instances disclosed a lack of ability in self-assessing the quality of their work, which itself is a source of ambiguity and open-endedness. Students use various techniques to do this from a context-content continuum.

The degree of similarity also acts as a feedback mechanism for students as they address their design tasks. Similarity in solution was often interpreted as 'correctness' of solution. Technical aspects, although important were only one facet by which students judged quality. Social comparison acts as a powerful tool to co-create boundaries and address the inherent open-endedness of design tasks with socially-constructed constraints.

Moreover, students justify their collaborative practices as a result of the context in which the design task takes place. Cameron Hooper holds beliefs in a strong collective identity, which encourages the collaboration of those belonging to the collective.

> Kind of like a mutual gain for the greater good. [Laughs]. Everyone is in the same boat. I hope the department appreciates that. I think it's unrealistic to expect that people won't work with people. - *Cameron Hooper*

Students' practice serves to benefit themselves, i.e. the individual, which also implies benefit for the collective. By working with peers, students are reinforcing a collective identity. Students participate in collaboration as it is mutually beneficial for all involved. All collaborating parties are able to benefit from the phenomenon as it involves bringing together individual resources for the benefit of the wider collective. Students are effectively acting according to a synergetic view of design. In reality, collaboration is enabled according to the degree to which it results in mutual benefit.

5.8.7 "That Doesn't Work": Peer Feedback Loops

Comparing allows for an iterative-feedback loop to be established which is used to progressively develop a solution. Collecting, sharing, comparing, critiquing and assimilating possible solutions are all processes by which students work collaboratively to develop quality in design solutions.

> That is when the other group that we kind of split into in phase 2 – when I started talking to everyone else who was designing the same unit as me – that's where we would talk to each other and maybe some of us had encountered the same thing. You could see what they were doing and whether they thought it was correct. That was really helpful. - *Sophia Duncan*

> So it was quite good working in this group because you'd come up with an idea and somebody would challenge – they'd say "that doesn't work" or you would say "I've got this" and then they'd say "that doesn't work". Or quite often somebody would think of something and then somebody would say "if you do this, then that makes it better". - *Natasha Douglas*

> I think it sometimes helped me understand it more if people were asking me questions because then I had to explain to them why I had done it, which reinforced it to myself – “that is why you’ve done it like that.” And sometimes I did change bits of it because they’d be like, “oh, I don’t know if that’s the best way.” And I’d be like, “oh, how have you done it?” And they’d be like, “oh, I’ve done it this way.” And I’d be like, “that’s definitely a better way.” - *Laura Dawson*

The accessibility of feedback on tentative solutions was an important factor that was identified as important both in group and individual phases. Being able to ask for feedback or a second opinion meant that causes of ambiguity and open-endedness could be constrained quickly, providing students with greater confidence in their developed work. Without regular feedback, students believed that their own design was subject to significant change should feedback be received later. Feedback is vital for students as they orientate and develop a solid foundation of their solution. Feedback promotes students’ progress as it encourages students to confidently further their design instead of remaining suspicious of their own work. This excerpt indicates that iterative feedback was a primary function of ALGs during individual detailed design and membership to such a group granted ease of access for students.

Students reported experiencing continuous peer-review of their design decisions from comparable peers. These questionings are a response from students when they recognize differences between their own work and that of a peer. There is evidence that the similarity of solutions stands as a proxy for quality for students. There then exists a strong psychological pressure for students to reduce differences and conform, perhaps brought about by a belief in a “single, correct answer.” Students are able to reduce differences by either conforming to peers’ conclusions or persuading peers to conform, with questioning used to strengthen personal justification for the former, or present evidence for the latter. When confronted with these scenarios, students responded by either acquiescing to the conclusions of the questioner or defending their design decisions.

5.8.8 Creative Minorities: Disadvantageous Originality

Where students are unable, or unwilling, to form groups to obtain feedback there is a significant challenge to be overcome and the result casts doubt on the quality of individually developed solutions.

> My grade wouldn’t be as good as the ones who work together because they had more people on it. But it doesn’t bother me because I don’t need my grade to be incredible to still be… Because my past grades. - *Will Ross*

Cain Bruce in the following rich excerpt, thoroughly described the struggle of maintaining individual originality in design and the associated reduced social validation.

> And yeah, it's… I think it's a sad situation where – within myself, when I'm thinking of making this design as original to myself as I can be – I feel like I'm putting myself at a disadvantage. When I feel like I want to design this entirely on my own, and come up with all my own, work it out on my own – do it all for me – part of me is like "no one else is doing that and they are all going to do better than you because they're all going to have the same method." And it's a scary thing, I've been wrestling with it a lot where I'm just like… I think of me being ahead of some people in this section is helping a lot with forcing me to be like "no, sit down and think about it." Because there's been a lot of situations where I get something, and I want to go over and be like "what do you think about this?" But they are not there yet, so I can do that, so I just have to reread a thing and try to work out. But there is a large part of me that is thinking you're putting yourself at a disadvantage and you're going to come out worse for it. - *Cain Bruce*

Cain, while, attempting to withdraw from the collective, found that complete isolation was neither desirable nor easily achieved, even in the individual phase design. Cain insinuates that if there were peers who were working on a similar task he would consider collaborating with them. This adds to the argument that a condition for comparing to occur is the similarity in task. Cain still opts to share his ideas with peers, as an avenue for gaining feedback on tentative solutions. This excerpt indicates that peers offer a valuable source of feedback for students as they work on significantly open-ended tasks.

This social comparison and feedback is a mechanism through which students constrain the open-endedness of tasks. In the absence of objectively 'correct answers' that students may be more familiar with in their course, students use subjective social comparisons to determine relative correctness instead.

Cain Bruce highlighted one motivation for engaging with the collective. There was the belief that individually generated ideas were best verified and approved through comparisons with the dominant opinions of the collective. Inherent in this belief was an interpretation of aggregate similarity as a proxy indicator for quality, which informs the notion of relative correctness. There was also, as highlighted by Will's comment, an expectation that collaboration with peers yields higher quality solutions for individual tasks. This perception may further drive students' tendencies to co-operate with one another and students may feel a compulsion to conform to the practices of their collaborating peers. Students designs become contextualised through the social processes of observing and comparing to peer-reviewed solutions. This suggests the presence of dominant 'collective'. These normative expectations of what constitutes quality in design solutions act as a source of constraint emerging from the social context. In this paradigm, solutions garner more validation according to the number of individuals participating in the collaborative production of the solution. The belief that such solutions are of higher quality means that collective design solutions create a social force emerging from the academic context of design, potentially resulting in a form of groupthink. Individual creativity in design may be subject to pressure to conform. The difficulty that must be overcome by 'creative minorities' is that of challenging dominant opinions and risking further isolation. The difficulty that must be overcome by 'creative minorities' is that of challenging dominant opinions and risking further isolation.

5.8.9 "How did You Manage that?" Exchanging Information for Feedback

One of the main aspects of students' behaviour during individual design was the exchange of information. Students reported sharing readily with others; and readily approached one another and engaged in these "information transactions". This related directly to students pre-design practices of proactively sharing and being generally receptive to requests for sharing.

> That definitely becomes, especially in phase 2 where the first reactor is proving a lot of issues, and I was sitting next to a guy from another group whose doing that part. And he got a Facebook message through from somebody who have not really spoken to at all, don't really know any of their friends either… "All right, they've done this, I'll try that." And he had that and then I went to my meeting the next day and Lauren, whose doing her reactor had the exact same method. And I was like "that got around quick". Somebody just came up with something, and now, that's what we have in our group. [Laughs]. And I was like "I know you didn't come up with that. Because you are messaging me after he sent that to him that you were struggling." But I'm not going to call out a member of my group being like "you didn't design that." But that, it's something that I'm trying to be as aware of as I can be on my part. - *Cain Bruce*

> And he was like, "how did you manage to do that? Because the data is not all there. Would you mind sending me the stuff you done?" So, I was like, fair enough, I can't be arsed explaining it to him, so if I just send it to him, then I don't have to waste my time which I need to use to further my progress. So, I just sent it to him, and I was like "let me know if you notice anything that's wrong with it." So, then at least I'm getting something back, rather than just giving away the three weeks of work. - *Will Ross*

As stated earlier, by providing information to peers, students do not simply engage in altruistic acts of generosity but anticipate some degree of reciprocation. Benefits of sharing aren't limited to equivalence of return, but other forms of 'paying back' exist through information transactions. In this instance described by Will Ross, the anticipated exchange was that the recipient would provide feedback on the work that was shared.

An important feature of design work is the development of adequate measures of quality. Students obtain feedback and evaluation of design through comparable peers. By sharing and comparing design, participants indicated that they were active members of using the design context to assist themselves in evaluating their work. In other words, students constrained the open-endedness of the design task by sourcing evaluations and feedback from comparable peers. By this process of comparing their work to others, students were able to develop both incremental progress and confidence in their tentative solutions.

Employing such behaviours represented a synchronised and self-organised approach to overcome shared problems. This “resourcefulness” is not isolated to the design project, but rather is enculturated from their prior experience on the programme. Students build strong ties throughout the programme, especially given the prominence of group work in the degree.

5.8.10 “Who Gets Better Answers”: Pooling Information and Effort

Pooling information and effort describes other critical functions served through students working with similarly-tasked peers. Such students simultaneously resourced relevant information and distributed this between one another and worked through problems together.

> And, I think that’s been better than any help, we’ve got so far from… So, I think that’s definitely is, getting over as we work together, we kind of use whatever little information we get from our advisers to work together and power through it and get as much done…
>
> **How is he getting on?**
>
> I think is all right, he’s getting one tomorrow – a meeting with the supervisor tomorrow as well. So, it will be interesting to see what he does. But, we’re basically going to come up with a list today, of things we want to ask and we will both ask tomorrow and then we’ll see who gets better answers. As I say, will work together with what we hear. - *Frank Hill*

> So we were kind of sharing stuff. And that was good because we knew that all – well, there were three of us – we’re going to be working hard – we were always in the James Weir together. - *Ellis Donaldson*

The perceived lack of guidance from supervisors strengthens students practice of collaborating with comparable peers. The collaboration with peers becomes an alternative method to obtain feedback, guidance and formative evaluation. By working with similarly tasked peers, students were able to maintain some of the similarities of working from the earlier group phase of design into the individual design. Indeed, this is the model often employed in group-based tutorials that are normative in modules earlier in the degree programme. Students were able to work together for a shared goal and offer mutual benefit by self-organising into these groups.

5.8.11 "Sharing Intel": Knowledge Gathering

Students suggest that their experience of other peers within their cohort as open and communicative. This meant that all forms of information, whether supervisory guidance, interactions, meta-information (such as task assignment – who is designing which unit), were readily distributed in, and between, networks of friends and acquaintances.

> However, I think that's important for phase two, the friendships that we've got, because we've, we're friends with different people… We've got different groups in the year, but we're also good friends so we can benefit from each other's like knowledge gathering from like, shared Intel. Yeah, which is good. And because we're not - because it's an individual project, we're not forced to work together. But because we're friends, we're still discussing it quite a lot. - *Will Ross*

> But there was also reports from previous years that got circulated. And then it was like, "who's got that one? That's a really good design." Like, "he's got that report, you should speak to him, he knows how to do that sort of thing." Which is helpful because it's good to have something to look at to compare what you had done. - *Laura Dawson*

> And because our whole year talk, we all knew what everybody else was designing. *- Phillip Easter*

The above excerpts represent a contextual factor of the studied participants who, as mentioned in the context chapter, have experienced a wealth of group-orientated pedagogical and social extra-curricular activities which may have contributed to the openness of communication mentioned.

Students frequently framed their own work with respect to content found in prior cohorts' reports. In this sense, prior cohorts' reports were effective models by which students could a) orientate themselves to the problem b) determine requirements by example and c) gauge quality of their own solutions.

Will Ross describes how, even though he did not form a group with similarly tasked peers during the individual phase of design, still engages with the wider collective. Here 'sharing intel' involves the act of pooling information from friends within the design group obtained from friends across different groups. Friendship is explicitly mentioned here as a condition, however in other reports friendship was not a necessary requirement to obtain information from the wider network. Contextualising Will's comments is his circumstances of lacking a similarly-tasked peer. This indicates that similarity of task, while a condition in design for engagement with peers about design tasks, pre-design socialisation is a separate condition that permits a similar engagement.

5.8.12 “Helping Each Other to Help Yourself”: Deviating Individual Goals

As students tended to view the supervisor as an evaluator of their design solution, students’ understanding of the requirement given to them by supervisors influenced the function and cohesion of students as they worked in their “quasi-groups” in individual design, especially as the particularities of the design solution progressed.

> And then outside of that, Arthur [member of other group] was one of the other people – he got told that he could make his U-values up from this sugar-based equation. But, when I asked Curtis [supervisor], he was like, “no, because you can really prove that empirical relationship.” So, I had to calculate mines through iteration which is horrendous in Mathcad. - *Aman Chowdhury*

Students contextualised their collaborative solutions in light of the expectation of their supervisors and other requirements, indicative of the adviser-as-customer approach to design. Students’ understanding of design quality developed through to their interactions with the individual academic supervisor, who acted as the evaluator of their design project. Academic assessment, then, formed the criteria by which design success was determined.

While many interviewees reported working together in quasi-groups for significant portions of their individual detailed design, variation in solutions nevertheless emerged. The relevance of, and comparability with, peers diminish, as a result of this individual adaption of design solutions, and the mutual benefit associated with peer-collaboration lessens. As students progress in their individual designs, they begin to tailor the general design to their individual constraints and requirements as developed from their appreciation of their wider design context and supervisors’ comments.

> So, did that, then me and Rayyan got to a point where we got the U-values and then we split apart. So, we work together in stages, and we got the ground-level built-up. So, we built the foundation together but then we built completely different buildings, I suppose you could say, and they were all kind of different. So, Rayyan stuck where he was, whereas I wanted to explore the multiphase nature of it and how it would work. So, I did all of that. And I used vacuum-based effects whereas he used all above atmosphere. So, I had to do some different design stuff for that. - *Aman Chowdhury*

> Just… Fair enough, we were all doing the same thing, but… It kind of felt like we were helping each other out – but we were helping each other out to help yourself out more than anything. So, people were actually being not helpful. And it was good to get started. But then I was like… But then when you had questions about your part – of the process – like your actual – because all the groups had done different things. - *Iona Mitchell*

> So, I think that's why it was good because we weren't doing – some things we did do the same, but at the same time other things we did do differently. Because… Because, obviously, your supervisors – what they wanted… - *Natasha Douglas*

Differences in supervisory requirements meant that, as detailed design progressed, the shared conceptual problem space shrunk and thus the associated cohesiveness of pseudo-groups were, too, weakened. The primary function of quasi-groups, then, was to reach a mutual consensus on the foundations of a given design solution, hence, the quasi-groups represented a social-mechanism through which students were able to orientate themselves to the design task.

Observed differences in supervisory requirements were also addressed by other means, other than tailoring solutions. One other student strategy was observed during supervisory meetings. Students would regard supervisory meetings as sites of negotiation where "other supervisors' requirements" were presented as arguments for negotiation in supervisory requirements.

5.8.13 "Snaking Each Other": Competitive Collaboration

Collaboration arises from the context of design, however, some students reported that their interpretation around evaluation in the educational context gave rise to tensions when collaborating as individuals.

> That was actually helpful. Everyone – you kind of didn't want to give too much away because if you found something really good and you kind of know that you're being benchmarked – you thought of want to keep it yourself. - *Sophia Duncan*

> But there was quite a lot of – within the whole year – a lot of… I don't know… "You've designed it that way." For people designing the same sections, especially. There were lots of… People were kind of snaking each other like, "oh, you've done it that way. That's a good way to do it." And then you'd be like, "if I've really done it the right way and there lots of people getting better ideas." Then you never knew if you'd done it the right way. - *Laura Dawson*

> One guy did it a completely different way… He shafted me, because he was like, he was stuck the same way I was in the first few weeks and then I just started making decisions on how to get my Gibbs energy and stuff… And then he didn't get back to me and he went with a different approach because he realised that… My – he said that he realised that my bit wouldn't work. So, I would have thought, "yeah, fair enough, let me know that. And then maybe we can move – then I will do something that will work." But he didn't, he just went away, did a completely different thing and told me by the time it was too late for me to go back and do it the other

> way, then he was like "oh yeah, by the way your way doesn't work." Like, "nice one mate." - *Will Ross*

> And they might say, "I wouldn't have done it that way." But then at that point you are too late into the design that you can't really go back to do it. But you just have to stick with your own idea and make it work. - *Laura Dawson*

> But I think we had the same supervisor. So, it's like, oh God, here we go… But I think I was one of the worst things, I just don't know why you keep talking to me about it. It's too late to redesign it or change it and I don't really know why. - *Natasha Douglas*

Students attempt to form a semi-permeable conceptual 'fence' around their collective solution. This fence has two primary functions related to solution development. Early on in the process, feedback allows challenges and ideas to be brought into a collectively validated solution and hence allow for improvements and positive progress. Second, as the solution develops, the primary function is to prevent substantially divergent concepts from intruding into working solutions as this could pose a risk to progress, or possible regress in design. If divergent concepts are recognised by the group as a valid challenge to the working solutions, the design solution must be rebuilt with this idea incorporated into it, subject to the practical limitations such as available time. This may also explain students' general fixation on data for their most recent design solution.

Another anticipation from some was the phenomenon of "snaking". Students may be inclined to mistrust feedback and evaluations given by peers where there was limited collaboration and so are unsure about the intentions of such comments. From this perspective students are inclined to believe that not all peers will provide feedback out of altruism, instead they may mislead them for their own relative advantage. In these instances, some may engage in behaviours which can be categorised as "differentiating design". These behaviours include withholding solutions, indicated by Sophia and Will; snaking each other i.e. giving misleading feedback, suggested by Laura Dawson; and isolating one's self from others, implied by Natasha Douglas.

Although collaborative in nature, participation with self-assembled peer groups did not entail absolute Information sharing. The expectation of relative evaluation with peers, although not a formal procedure for evaluation, results in a competitive undertone to collaboration. Students can selectively withhold information to position themselves evaluatively better than their peers. This competition stands in tension with collaboration. In the context of these self-assembled groups, competition entails differentiation from peers, whereas collaboration entails emulation with peers. Although elements of both are present throughout the project experience, students tended to transition from greater emulation to greater differentiation as they progress through design. This is a pragmatic solution to the tension which arises from the competitive-collaborative context through the use of comparisons as a mechanism throughout.

Although formalisation of the collaborative process does not always occur, students maintain communication and correspondence with comparable peers. Students communicate and monitor the progress of others and compare their own progress relative to that of their peers. Even in instances of negative interactions with peers, communication may still be maintained, although in such cases communication may be limited in a strategic manner.

5.9 Summary

This chapter examined the findings from interviews, offering a detailed analysis of the various salient codes that emerged from the participants' experiences in the CE design setting. It started by situating the reader in the context of the participants' pre-existing conceptions and social norms that influenced their approach to design tasks. Following this, the discussion moved into the specifics of how participants interpreted and responded to the design brief and the criteria laid out for evaluation, providing a foundation for understanding their subsequent design processes.

The analysis then explored the complex dynamics of design supervision, shedding light on the interpersonal and instructional dimensions that shaped the learning experience. Technical aspects of the design process were also critically analysed, revealing how students engaged with tools and methods, and how these elements contributed to their design development. The chapter went on to investigate both group and individual phases of design work, highlighting shifts in collaboration, creativity, and decision-making.

Through a careful examination of these varied dimensions, the chapter underscored the interconnectedness of social context, supervision, technical engagement, and design practice, painting a nuanced picture of the participants' journeys. The inclusion of detailed excerpts allowed for a more vivid portrayal of these experiences, emphasizing the depth and diversity of perspective that emerged in this study.

Chapter 6. Literature Data Analysis

6.1 Introduction

This chapter introduces the extant literature as additional data for further investigation and incorporation into the existing analysis. The chapter covers a review of literature which is contextually close to the subject of this thesis, namely engineering students working on design activities, and compares the developed accounts and analyses from other studies to these contexts which are distinct from the design project at the University of Strathclyde.

This chapter begins with a brief overview and description of two studies, Morgan (2017) and Goncher (2012) which were explored. Each study is contextualised before the presentation of analysis which is presented like the previous chapter - concepts have emerged from direct reference to relevant excerpts from the work which have been grouped and analysed. In addition, reference to the analysis in the preceding chapter is included to demonstrate the relevance of these concepts and how these contribute to new dimensions the analysis. Through this approach the developed analysis becomes more rigorous and increasingly abstracted from the singular case, in order to develop a more robust ‘grounded’ theory. Finally, the chapter closes with a summary of the prominent codes for the studies.

6.2 Data Rich Qualitative Studies of Engineering Design Projects

Among studies in the field of engineering design in higher education, there is a limited pool of studies which involve a thorough qualitative exploration of students’ experiences as part of group projects using rich data collection such as observations and interviews. From these, the studies conducted by Morgan (2017) and Goncher (2012) are examples of work which offer significant detail which make these good sources for secondary data for further exploration of the emergent analytic themes from the data collected as part of this thesis. The research settings of these works and that of this thesis are summarised in Table 1.1. Morgan’s (2017) study incorporated two studies, one involving year 1 students and the other involving year 5 students, Design Project 1 (DP1) and Design Project 5 (DP5), respectively. Goncher (2012) explores a first-year design project as part of a course titled Designing Sustainable Engineering Products (DSEP). These acronyms will be used for reference, consistent with the original works.

These studies demonstrate a degree of variability across the various elements that make up educational design projects. By incorporating these studies into the existing analysis from the Chemical Engineering (CE) design study, the robustness of the grounded theory presented is strengthened.

Table 1.1 Summary of design project under study for this work, Morgan (2017) and Goncher (2012)

Research Participants' Context	Sharif (This Work) [CE]	Morgan (2017) [DP1/DP5)	Goncher (2012, DSEP)
Country of Study	UK	UK	US
Title of Course	BEng/MEng Chemical Engineering	MEng Mechnical Engineering (DP1) / MEng Engineering Design (DP5)	Engineering Course
Year of Student's Programme	Year 4	Year 1 (DP1) / Year 5 (DP5)	Year 1
ECTS Credits	30	5 (DP1) / 20 (DP5)	4
Duration (weeks)	11	8 (DP1) / 20 (DP5)	8
Number of students per group	6 or 7	8 or 9 (DP1) / 4 (DP5)	4
Main Design Output	Process	Product (DP1) / Process-System (DP5)	Product
Assessable Components	Reports, group presentation, HAZOP, peer-assessment (2016)	Reports, sketches, peer assessment (DP1) / Reports, presentations, individual viva voce exam, peer assessment (DP5)	Reports, demo, sketches, peer-evaluation

Although not directly considered as part of the following analysis, the approaches to the qualitative research for each study are summarised below in Table 1.2.

Table 1.2 Comparison of research approaches for this work, Morgan (2017) and Goncher (2012)

Research Approach	Sharif (This Work)	Morgan (2017)	Goncher (2012)
Methodology	Grounded Theory	Ethnomethodology; Case Study	Case Study
Analytic Techniques	Constant comparisons Initial coding Focused coding	Thematic Analysis	Within-case and cross-case analysis Nested Theory of Structuration
Data Sources	Student Interviews (audio recorded and fully transcriptions) Non-participant student-supervisor meeting observations (audio recordings and field notes) Secondary data of other studies	Non-participant student team observations and stakeholder meeting observations (Video Recording and Full Transcripts for DP1 / Selective transcripts for DP5)	Non-participant student team observations (Video Recordings and full transcripts) Semi-Structured Focus Group Interviews (Video Recordings)

The works of Morgan (2017) and Goncher (2012) are discussed in turn, each beginning with a brief description of the context for the investigated design projects followed by a discussion of the salient analytic codes. The emergent codes were developed with the data available from the original works using techniques from the grounded theory method as outlined earlier.

In Morgan's (2017) work she explored two design project instances, both are discussed below and analysed according to the codes developed in the previous analysis chapter. All names in the transcripts are pseudonyms for observed students, and instructors and supervisors are indicated in parenthesis where relevant.

6.3 Morgan (2017) Design Project 1 (DP1)

6.3.1 Context

The DP1 project investigated by Morgan (2017) related to first year MEng mechanical engineering students designing and building a "vending machine which stores and dispenses on command a standard opaque plastic cup (White polyethylene) from a vertical stack or at least 10 cups" at the University of Bristol, UK, in 2013. Students on the 8-week DP1 were also provided with further specifications and constraints such as the inclusion of a programmable controller, use of a 12V DC power supply, budget of £100 etc.

A single group of 8 students was observed at weekly design sessions by Morgan (2017) over 7 sessions as part of DP1. The students were given the pseudonyms of Abdul, Anita, Clare, Henry, Joe, Mikko, Nathan and Omar. Others names that are referenced in the study are Chris (group supervisor) and Jonathan (DP1 coordinator).

6.3.2 Designing a Functional Prototype

The requirements for DP1 described above can be compared to the design brief for CE design:

> Your design group has the task of producing a preliminary design of a process to convert raw sugar beet to anhydrous ethanol. The finished product must meet the EU specification for de-natured ethanol EN 15376. The design output is to be either 10,000 m^3, 100,000 m^3, or 1,000,000 m^3 of anhydrous fuel grade ethanol per year… Your design must conform to the latest environmental standards and must aim to minimise the discharge of effluents to the environment and maximise the utilisation of inputs." (CP407 2016 Design Brief)

It is apparent from these design specifications that DP1 involves a more focused scope in design compared to that of CE design, but both shared a general specificity of what was required. In addition, the main project output is a working prototype of the cup vending machine for DP1, whereas CE design involves the proposal of a process. Inherent, then, is a degree of abstraction involved in the design for chemical engineering students. The inherent ‘physicality’ of DP1 is clear through many interactions between students, such as the following excerpt.

> You’ve either got a beam like that (demos with hands) and when something gets in the way of the beam it senses the thing. Or you have them looking the same way (emitter and receiver) and once something is in the way some of the beam gets reflected back to the receiver.” Abdul says “It would be quite difficult to have it reflected back off here (he holds up the cup). (p. 74)

There is a concreteness to this design context that makes for explanations and problem definition to be tied closer to physical objects. In contrast, chemical engineering design (and other process related design) is less tangible and more abstract. Given this focus on process for students in our study, there is a restriction on the available approaches for defining and solving the design problem. Therefore, this may explain why there is greater reliance on abstract methods of engagement with design, with more focus on hypothesis generation; abstract reasoning (e.g. use of mathematics); and reliance on models of design.

A significant difference between the studies is that of ‘building’ and ‘testing’ which conceptually becomes more difficult for chemical engineering student since their design solutions cannot be ‘built’ and ‘tested’ in a direct sense. This proves difficult as experimentation (i.e. testing, as described here) is not an avenue through which students can obtain immediate, iterative feedback. Students are able to obtain feedback through mathematical means, however this is again relatively abstract when compared to DP1.

6.3.3 Coming Together

Morgan describes the students first coming together as a group:

> They tentatively sit down together but no one speaks. These students do not appear to know each other. (p. 61)

Another distinguishing feature was that the DP1 students in Morgan’s (2017) study are first year students, which contrasts with the fourth year students in CE design. There is unlikely to be as thorough an awareness of reputations and expertise of group members for students early on in their programmes. As mentioned in the analysis of CE design, not all students knew each other well, but the general tendency was for students to know *of* each other and associated reputations that carried forward into the project.

The supervisors present at the team sessions in DP1 explicitly advised students to select a leader. This suggestion from the supervisors sensitises students to responsibilities and roles for group members. In the CE design study, the recommendation that students elect a leader was seldom explicitly suggested by advisers, however, some supervisors did request that advisory meetings were chaired and minuted by appointed members (and some went as far as to request these roles were rotated at each week's advisory meeting).

> Clare makes the first move and volunteers herself as team leader, if no one else would like the role. She's not pushy about it and the team seem happy for her to do it. (p. 62).

This aligns with the CE design experience for which few participants suggested that their group formalised leadership responsibility. This stands in contrast with the report from Sarah French's group in the CE study where Sarah and Amy competed for leadership - ending in Sarah ultimately resigning from the leadership role as there was an awareness that continual challenge may give rise to tensions with the group.

6.3.4 Sharing a Physical Space for Design

Much like the CE design, the DP1 students in Morgan's (2017) study congregate in physical spaces where other groups work too.

> Six of the teams however make their way out of the CDO and up to the first floor, to a much smaller studio space, studio 1.7… It is a medium-sized teaching studio space, with a high ceiling, which comfortably accommodates the 60 students now in it, arranged as six groups around six clusters of tables. (p. 60)

> The group are sat around their usual table. They are annoyed that Nathan and Abdul aren't there yet, they don't think they can be sick. (p. 100)

Again, consistency in physical location and presence is considered critical for effective group work in design. This can be complemented with the concept of "being there" (section 5.7.9). This is particularly emphasised at significant points such as being together work for submission - a frustration shared by Sarah French in our study with a member of her group, Adam. Interestingly, in her circumstances, Adam too was not present for the submission. This was interpreted as a form of free-riding and ultimately resulted in the group negatively peer-reviewing Adam. In contrast, Will Ross describes two members of his group who did not contribute to the submission significantly, "were there". Mere presence plays a role in group perceptions of members' commitment to the group.

6.3.5 Dividing labour

Division of labour is a significant aspect of the DP1 students design project and, like the CE design, its importance is highlighted by supervisors.

> Then [Chris] checks with the group… "So, you've got ideas for the cup dispensing? You've got ideas for the door? You've got ideas for a cup-store of some sort? You've got ideas for how you're going to hold the cup once it's been dispensed?"

> They all say yeah. “And have you been talking about how you’re going to divide the work up between you?” “Not yet” says Joe (p. 67)

Chris (supervisor) explicitly suggests that work is divided up between members of the group. This followed from a discussion on the ideas for the various operations of design. In comparison, CE students in their design are also explicitly encouraged to divide work among group members, however, the division tends to be around sections of the design report. The ‘product’ of design is the design report submission, and not a physical design. There is suggestion of ‘components’ of design - in this case the components are functional aspects of the design which are generally distinct, whereas in the abstract CE group phase of design the components are interlinked attributes of design (e.g. location, raw materials, bio/chemical transformations etc.). This contrasts to the individual phase of design, where unit operations or sub-processes within the process are the divisible components - which is closer to the division observed here.

> The group has naturally separated out into working pairs. Nathan and Omar continue with the dimensioning of the external casing, Mikko and Abdul are dimensioning the door, Anita and Joe are discussing materials, and Henry and Clare are talking about control systems. (p. 93)

Generally, their division of labour tended to involve sub-groups and not individuals, but not always. In the following excerpt division of labour is suggested, as opposed to being formally assigned.

> Joe asks Anita “Are you happy to do the economics stuff? She nods and … says, “it’s just general stuff… we need to specify materials and components (she gets up and leaves the table, and comes back with a form)”. (p. 96)

It can be observed that the division of labour can involve a relatively informal approach. This is supported by the approach taken by some CE students. This may be related to students attempting to balance the role of relative unfamiliarity with peers. There is a tendency to approach with indirectness - to suggest rather than direct. Being overly direct and ‘managerial’ was perceived unfavourably, with most students preferring a relaxed approach to division of labour, especially related to group stages. In contrast students were considerably forthcoming when dividing labour for the individual detailed design, which makes sense as the responsibility is student’s own, and no longer shared with the group.

6.3.6 Orientating to the Design Guide

Another process established early on and continuously throughout the design project was the process of designing to the guide (section 5.4.1).

> Clare clarifies with the others… "So, we're not yet doing like… ideas of design… or are we?" She checks the project guidebook which is open on the desk next to her. Joe "We need to go through the specification… so if we have a look at the spec…" They agree, and turn to the 'spec' in the guide. Anita reads aloud from the guide… "Each group is to design and build a vending machine which stores and dispenses, on command, a standard opaque plastic cup, from a store of 10. (p. 63)

> Chris "Anyone handling the business plan?" Clare "What is the business plan?" Chris "Well it says in the guide, but what we're encouraging you to do is think about how this fits into a business context. (p. 95)

In the two examples it can be seen in the former how the group naturally orientate to the design guide and in the latter, it can be observed that Chris (supervisor) sign-posts to the guide. There was essentially an attempt to relate design to "real" contexts by encouraging students to think about how such a design would impact a theoretical business process. This encouraged students to think beyond the specifics of design. In a similar vain, CE design involves the considerations of the business case for the proposed design by considering economic analyses, life-cycle assessment etc.

It can be observed that the guidebook is repeatedly referred to throughout DP1 and functions as an orientating tool for the group. Not only do students use the design brief to orientate to design, but also to orientate to the wider context of design, namely that of design as an educational activity. It is likely for this reason that students are somewhat surprised at how they will be assessed (50% for drawings).

> Joe "I think we ought to find out about how much the innovative side of it worth… in terms of the marking". "Anita reads from the course guide… "10% for original ideas." Mikko "Drawings are worth 50%… so let's choose something that's easy to draw!" Joe "My tutor was saying that that is one of the main points of this exercise basically… the drawings." Clare "I'm not surprised to be honest". Abdul "You mean 50% of this project is for the drawings?? Wow." Clare "Not these drawings (points at their rough sketches), the engineering drawings". (p. 86)

It can be noted that the grade weighting informs students decision making - and acts as a significant educational constraint in their design solution. Up until this excerpt, students discussions had focussed on perceptions of feasibility, cost-effectiveness, and business cases. Students had effectively 'bought-in' to the design activity as 'real' design. At this point they turned to the 'real' context of design and that is the academic exercise of design. In this way, the educational requirements for DP1 are outlined relatively clearly for students. Similarly, students in CE use the design brief to justify their inclusions and this also informs students behaviours and approaches to matters such as labour division.

> Henry runs through the itinerary for this week to check they've done it all… "Identification of subsystems and requirements, sketches of possible solutions and identify responsibilities of the group". They agree that they've done all of them. (p. 84)

> Joe "We seriously have to make up our minds today about these, which is quite scary." (p. 80)

Note that the expectations of key outputs from the sessions are included in a 'recommended schedule of work' provided to the students taking DP1. This provides explicit guidance to students on the inputs, activities and outputs at each of the 7 scheduled sessions. This degree of explicit guidance is absent, aside from deadline for assessed submissions, from larger projects such as the CE design project which requires students to determine what needs to be done and achieved for themselves within the timeframe until submission. Advisers do provide a degree of guidance on general progress and will at times intervene if progress is deemed insufficient to provide more explicit guidance. In any case, the approach to 'scheduling work' is much more fluid and ambiguous, and hence more ill-defined.

6.3.7 Seeking out Models of Design

Similar to CE design, students in DP1 also highlighted the importance of models as part of their designs.

> Then Omar asks, "Does anyone have any idea how these things are done in real life?" Clare isn't sure but thinks it is a "good thing to google". (p. 65)

Models of design are something that the students consider here too. Existing solutions are useful to students as they demonstrate one possible approach to the design problem. However, such solutions can over-constrain the design problem and result in conceptually hindering students development of the design problem through their creative insight. Existing models, given that these have been potentially commercially realised, dominate students design problem definition. Instead of being a possible design solution it is possible that this can become *the* design solution for students.

> Anita has been looking at clips of mechanisms on YouTube and Henry has been looking at patents… "I looked online to see what I could find and I got this patent from the U.S. patent office, for an automated drinks dispenser…. But I don't understand it at the moment. It's all labelled with numbers… but there's nothing that says what all the numbers are." (p. 71)

Similar to CE design students, there is this exploration of existing models of design. This has led students to patented solutions, similar to those discussed here. In CE design, deciphering patent language was also a recognised challenge. There is an authority placed on such models of design. Given that such designs are published and documented, students perceive these as tenable and working. Ultimately, such design offer a fixed solution which resolves the ambiguity inherent in the design problem. The students here, however, are bounded by the requirements that they must build the solution subject to a budget constraint - a discussion which follows and culminates in disregarding the patent. This means that ‘practical implementation’ factors into their design requirements - a feature that is relatively less important in chemical engineering design of a process which does not entail a ‘build’ phase. Importantly, patents themselves can be ambiguous and intentionally omit details, so being able to work with such designs can become challenging for chemical engineering design students, since concerns around insufficiency of data and inference of details can become significantly impacted by following such models.

6.3.8 Seeking Supervisory Clarifications

At the onset of DP1, the following interaction took place between Chris and Henry (supervisors) and the DP1 group.

> Chris comes over to the table and just watches. Henry asks the group about coding the programmable controller, wondering if anyone has any experience with coding. No one has. Chris steps in and asks, “Are you listing out the sequences of operations… is that right?” They confirm that they are. Chris… “That’s very good and I think that’s exactly what you should do (p. 63)

At this early interaction in the DP1, the supervisor provided feedback on students activities, in this instance without prompt from the student. Such unprompted feedback was not observed in the CE meetings or reported by participants of the study, perhaps owing to supervisors’ lack of direct observation of student groups during their separate design meetings. Affirmation from supervisors was a feature of design that CE students attached much importance to, and the absence of which led to significant distress. An example in the CE study was the experience reported by Frank Hill whose group’s requests for feedback were met with consistent dismissal from their supervisor. Without some feedback, or confirmation, students are faced with compounding ambiguity of their approach to design.

Similar to CE design, the DP1 supervisors also act as advisers to the brief and outline what the ‘rules of the game’ are. Such as the interaction between Clare and Chris (supervisor), where Clare elicits a clarification on one of the project outputs.

> “On the outputs for this session, one of them says ‘draft schemes for actuating and sensing’… what does that mean?” Chris “All it is, is listing what actuators you think you’ll actually use, which sensors… all of the programming and sequencing you don’t have to worry about for now.” Clare “OK that’s fine then.” (p. 87)

This falls into students concerns for “defining the design requirements”, a process which often was impacted by supervisory willingness to engage with this by providing feedback. Other examples of clarifications involve clarification on permitted approaches to design. The following is an interaction between Henry (student) and Chris (supervisor).

> Henry asks Chris if they’re allowed to use ideas from patents. Chris “Interesting… it’s a bit against the spirit of it… and obviously if you were doing something commercially then you couldn’t as you’d be contravening a patent, but for an undergraduate exercise they’re not going to find out and sue you… but to some extent it’s against the spirit of it […] I’ll get advice from Jonathan.” (p. 72)

Here we have another instance of context constraining design approach, in the context of education the supervisor suggests that using patents for ideas is a possible option, but in commercial design this would be explicitly forbidden. The supervisor returns.

> Chris comes back to them with an answer about the patents… “You may NOT use a patented solution, however if you hadn’t told us you might have got away with it…!” (p. 73)

As expected, copying an existing solution, specifically a patented solution in this case, is prohibited. Interesting here is that Chris (supervisor) suggests that if students had not asked for permission they would “have got away with it”. This is something that is most likely learned throughout a degree programme. In our study there were several instances of students “refraining from disclosure” of information to supervisors. This ranged from disclosure of “known deficiencies” in design solutions, sources of information, and group dynamics.

6.3.9 Presenting Ideas and Getting Feedback

The vast majority of the discussions that took place between DP1 students involved them proposing design solutions and providing or receiving feedback.

> Joe has also come up with another cup separating idea since last week, which he explains to the group… (p. 72)

> Joe asks Mikko why he likes the idea more than the sliding door. Mikko “I know it’s more complicated, but I think it’s more interesting.” Abdul “It’s more unique. I think the sliding door is just a safe idea.” Mikko “And I like the idea that the rotating door doesn’t need to be reset after every operation.” Abdul “I like the rotating door idea as well… it’s always just easy to go for the safe option… and I think quite a few groups have done that, and ours would be a bit different. (p. 82)

In Morgan’s (2017) study of DP1 students, the most frequently reported observed activity students engaged in involves presenting ideas to the group for feedback with multiple members taking opportunities to present ideas. Feedback took the form of enquiry (asking for more information); positive appraisal; or cautioning, usually the discussion is fluid and feedback blends into different types through iterative review/discussion. There is a fluid back-and-forth discussion on various design aspects through much of the transcripts of the design meetings. This fits into the notion of “Bouncing off ideas and Gaining Different Perspectives” (group phase) and “Iterative Peer Feedback Loops” (individual phase) in the CE design. It can also be noted in the above excerpt how Abdul challenges the dominant solution across the other design groups. From the CE design study, similarities can be found in the account of Cain Bruce, whose group also demonstrated “being ahead of the curve” in relation to the dominant solution across groups.

This type of presentation of design solutions for feedback was not limited to students only, but also supervisors too as demonstrated in the following exchange between the DP1 group and Chris (supervisor).

> “So, our first idea is an arm that swings 180 degrees… just one of the first things we came up with (they all laugh). There’s an arm that just grabs the cup off the top of an upturned stack. We thought it’d be quite difficult and expensive to manufacture a robotic arm that grabs and releases a cup, and also it takes up quite a lot of space…” Joe “I think we had issues with the maintenance… repairing it”. Chris “Well it’s the first one I’ve seen like that, so that’s good!” Omar “Our second idea was… like an inverted caterpillar track… where the teeth fit in between the cup lips and push the bottom cup off”. Chris says, “Not surprisingly I’ve seen that one a lot!” (p. 74)

Presenting of solutions for feedback described here. Note that the supervisor’s comments on the ‘originality’ of the two designs - with one being more dominant across the groups. The supervisor offered positive feedback around the originality of the “robotic arm” solution, even though it is not realisable. The interaction does provide students feedback on the supervisor’s preferences and values surrounding design. By understanding that the supervisor values originality, this ultimately informs the students choices regarding subsequent design decisions. Nevertheless, dominant solutions and comparisons persist throughout the design process.

6.3.10 Comparing with the Collective

In Morgan’s (2017) third observed session of DP1 students the first explicit comparison with other groups are made by Clare.

> Clare “The thing is, other groups using a motor are using it to drive several things together…” (p. 81)

This is the first reported instance where the group have compared their design with that of others - the language suggests that Clare is comparing with several groups and not a single one. In this case, comparison is used to determine the ‘correct’ uses for a design component (i.e. motor in this case) and it appears as though there is a strong collective position on this. Clare invokes this idea of collective norms to gauge the feasibility of the proposed solution and as a negotiating tool with Abdul.

Comparisons serve a similar function in CE design - it was used as a social process to determine appropriateness and quality. This can be compared with how students approach comparable peers in the individual and group phases to determine their approach and negotiate/reduce differences by presenting ‘collectivised’ solutions. Clare at various instances cites another source to draw comparisons from, the prior year’s winning design solution.

> Clare “I’d kind of like a motor, but I think then we’d need to use the motor for everything. That would be my view. The group that won last year, they used a motor then integrated it with all the other things”… “I just think that a motor is the most reliable way to do it.”. (p. 81)
>
> Clare tells Omar, Anita and Nathan “I spoke to a guy from last year who won it, and he showed me his design, and basically they just used one motor to power both things. It looked really weird… they had this thing, that they’d bought (she sketches it), and it’s got one ridge that goes up like this, and that came out and took the next cup down, and then at the same time it was parallel with the rotating thing at the bottom…” Omar “They also had a rotating door?” Clare “Yeah, they had the rotating platform with the fixed door, and they both got powered by the same motor.” Omar “Why didn’t we do that?” Clare “I did try and introduce it but everyone shot it down! I couldn’t really say ‘but I KNOW that it works’!” Anita “You know we did have that idea down initially…” Omar “That sucks!” Clare “Oh well”. (p. 97)

Comparing with previous cohort’s again reveals itself as a significant orientating and source from which quality is determined and feedback gained on tentative design solutions.

Clare compares several times, in the final excerpts, to previous cohorts. She compares the approach taken by the ‘winning’ team as an indication of quality of solutions and feedback on appropriateness of the proposal made by Abdul. Ultimately, these considerations (i.e. how others groups design) convinced Clare that a particular design solution is more ‘reliable’. In CE design, several participants reported how ‘sharing intel’ was common, and this was confirmed in supervisory meeting observations too. This included entire design reports and information on the quality of such reports (see section 5.8.11).

Contextual comparisons with other groups (both within their cohort and with previous cohorts approaches) forms a critical source of feedback for design decisions.

> Joe asks Mikko why he likes the idea more than the sliding door. Mikko “I know it’s more complicated, but I think it’s more interesting.” Abdul “It’s more unique. I think

> the sliding door is just a safe idea." Mikko "And I like the idea that the rotating door doesn't need to be reset after every operation." Abdul "I like the rotating door idea as well… it's always just easy to go for the safe option… and I think quite a few groups have done that, and ours would be a bit different. (p. 82)

Note how Abdul (similar to Cain Bruce in the CE design study) challenges the emerging dominant solution here and was subsequently met with resistance. However, the degree to which students are aligned to the educational context of the design can impact how the students approach these occurrences.

> Henry "Yeah, I just think rotating door is gona get us more credit, it's more clever. Sliding door… it's like 'ok we need a door, let's just make it whatever', whereas rotating door is actually quite cool." (p. 84)

There is an understanding that creativity offers more academic credit. This offers an insight into how students approach design and how the educational constraints can have a meaningful impact on students' behaviours as they attempt to resolve conflicting 'design discourses', in the phrasing of Morgan (2017). While Morgan focuses on the paradox emerging from conflicting design discourses emerging from the university design and those of a commercial design, these excerpts reveal that the competing discourses *within* the university settings can become among the central design paradoxes to resolve. In the CE design study, this paradox is eloquently summarised by Cain Bruce in a moment of reflection.

> And yeah, it's… I think it's a sad situation where – within myself, when I'm thinking of making this design as original to myself as I can be – I feel like I'm putting myself at a disadvantage. When I feel like I want to design this entirely on my own, and come up with all my own, work it out on my own – do it all for me – part of me is like "no one else is doing that and they are all going to do better than you because they're all going to have the same method." And it's a scary thing, I've been wrestling with it a lot where I'm just like… But there is a large part of me that is thinking you're putting yourself at a disadvantage and you're going to come out worse for it. - *Cain Bruce*

In both accounts both these design discourses and resultant paradox emerge from the university setting. The prevalence of similar design solutions offer a degree of affirmation, whereas the credit in the evaluation criteria offers some motivation for taking an original, and hence divergent, approach. There were several other indications that other students experienced this in the CE design study such as Natasha Douglas, who reported her 'interrogation' for her design decisions by another student whose solution was different to hers, and also in casual reporting outside of the design setting. In one, unrecorded interaction, a CE student who had completed CE design asked the primary researcher the following question (not verbatim): "Did anyone tell you about how you might be in the James Weir computer labs and glance over and see someone else's work for a moment and your heart would sink because you think you have done it all wrong?" These accounts suggest that this paradox was relatively common across the cohort.

In the DP1 study, another factor which contributed to the resolution of this paradox for the students in the DP1 students is that of the affordance for unrealisable design solutions in the context of evaluation.

> Joe "OK, I'm just gona ask about how they weight the innovation, like whether or not we go for something safe, or whether we go for… like if it does screw up, will we still get marks? Or will they just be like 'it doesn't work'." Clare "I think they're just gona… even if it doesn't work they're gona give us marks". Anita "Yeah, the actual making, building of it is only 10 % (she's looking at the marking scheme in the course guide) so it's more on the concepts and the drawing and stuff." Clare "Yeah, it's more about the process rather than what happens at the end." (p. 87)

This deeper understanding of the brief can encourage students to take a perceived 'riskier' and more creative approach. Ultimately, such affordance for design failures grants students more appetite for failure, provided there is minimal negative impact on evaluation.

6.3.11 Minimising Risks

Students, when confronted with decisions, can be confronted with unknowns and possible issues as a result of decisions being made that 'lock-in' the design. The following excerpts from DP1 highlight this:

> Joe "I'm very risk averse at the minute, I feel like we've only had three weeks to come up with, and fully mature ideas, which we're now gona have to spend the next 4 weeks fully designing, and I feel we should do something safe in case it all goes tits up." (p. 84)

The feasibility of design is a factor in students decision making. The 'safeness' in design makes it an attractive option.

> Joe "yeah, yeah, but I just feel like there's a lot of work there." Henry "well no, cos you have the motor, say it's at 60 rpm, and you gear it down so that its sufficiently slow to turn the platform, or as slow as you like…" Joe "Yeah OK, I'm just very scared that we're gona get to a point whereby we're stuck. We'll come across an issue we hadn't thought of… on any of the designs, and then we just go 'oh, what are we gona do now?'" Henry "But how can you avoid that? Cos you're going to have to choose one of the designs… and that's the problem-solving to do with it." Joe "I just feel like we need to de-risk as much as possible, so have like the least number of moving parts." (p. 84)

CE students also attempt to forestall future issues in CE design through various approaches. This can be observed in the study of CE design with students opting to select models for designs as a means to reduce possible future risks in design, similar to that of DP1 some of whom cite models of success from previous cohorts as justification. ‘Projected risk’ appears to be a design factor and a criterion for evaluating design for students in general. CE students also factored in how accessible detailed would be too, e.g. by ensuring there was sufficient data for downstream detailed design.

6.3.12 Deciding Democratically

In the DP1 study there was an instance of students attempting to make key decisions their design solution with no clear agreement being reached.

> Clare “I like the rotating door, but does it use a motor?” Abdul “No, that’s what I was saying… use a solenoid”. Mikko explains “We’re just debating whether to use a motor or a solenoid and Abdul is pushing for solenoid.” Abdul “I’m only pushing for solenoid because we haven’t considered it… were just going ‘oh it doesn’t work’, but we haven’t actually thought through a solution to it. We’ve just gone ‘oh that’s a problem’, but haven’t thought of any reason why you can’t fix it.” Joe “Yeah, I’m really sceptical of the actuation on this one, unless you use a motor”. Abdul “The only reason I was suggesting it was because it’s half the price of a motor… and we haven’t even considered all the costs of the materials”. (Page 81)

Design decision making here was ultimately left to the entire group by way of voting for a majority.

> Joe suggests that “Maybe we should go around the table and see what each person thinks is the best idea, or most feasible.” Mikko “A democratic vote!” Abdul “And you’ve got to give a reason as well, you can’t just…” (p. 82)

In CE design, participants reported that in group phases, sub-groups often arrived at conclusions and presented this to students. There were no explicit reports from students about such instances of disagreement within groups on design decisions. Generally, sub-groups or those responsible for sections would share their findings with the wider group and these were accepted or feedback would be given leading to revisions. There was a degree of group alignment on critical decisions, although, there were no instances reported with such a significant split. Nevertheless, the decisions generally underwent informal appraisal through the wider group.

6.3.13 Professionalising Design

Students in DP1 did not only address design challenges with reference to the educational setting but on occasion deferred to the conventions of professional/commercial design - in the following excerpt, this is described as “actual” design.

> Anita “Do we need to find out about that? Whether we actually need access for maintenance?” Joe “I think it was just to see it” Clare “It’s just an observation panel”. Omar “It would be good if we could though… it’s poor design otherwise. I think when they mark it, it’ll be based on this being an actual (commercial) design which could be implemented in any practical way, and it can’t if you can’t actually maintain it. Anyway, we thought of a few ideas for a kind of door for both designs, and a couple of different ideas on you’d assemble those”. (p. 96)

Students use expectations of professional design to judge whether they should include certain requirements into their final design. This is akin to students in CE referring to ‘industry’ when making decisions. However, there is an awareness that the academic requirements for design offers dispensations that would not usually be available for commercial designers. Students experience this as a tension in design - professional/industrial level design is still the ultimate goal and so an educational design dispensation is treated cautiously. At times, students may hold the belief that commercial/industrial design considerations will override the educational requirements of design. It is also true that students understanding of principles of ‘good design’ can override such educational limitations too. This is similar to how both Ewan Murray’s group member and Billy Reynolds, in the CE design study, sacrifice what they considered to be creative and insightful design considerations in order to satisfy the report length restrictions. The students in DP1 revisit the same aspect of the “observation panel” described earlier in a later meeting.

> Joe and Omar debate how important the design of the observation panels is. Joe thinks it’s a minor thing, not to spend much time on. Omar thinks it’s a key requirement and it should look good. (p. 99)

Students can have different ideas of the importance of certain requirements. This exemplifies students’ expectations of what design requirements ought to be (i.e. professional design practice) against design in the context of learning (i.e. learning design practice). When conflicting, students must determine which should take priority. This is also indicated when Spencer Jennings shares that many peers deliberately exceeded word counts, but he himself did not, since the educational requirements must be met. Spencer’s peers instead worried about the completeness of design which overrode the educational requirements in favour of what is considered to be a more representative design.

6.4 Morgan (2017) Design Project 5 (DP5)

6.4.1 Context

The DP5 project investigated by Morgan (2017) involved observation of a group of four final year MEng students in an Engineering Design programme undertaking a design project at the University of Bristol across the 2013/2014 academic year. Morgan states that "DP5 constitutes a third of their credits in the final year [and] [a]longside DP5, they take several units" (p. 102) and that this DP5 involved the "development of a detailed design requirements specification in collaboration with [an] Industrial Sponsor… followed by a Conceptual Design Stage and then a more detailed development process, involving the construction of virtual or physical models/prototypes of the final product or system." (p. 102). DP5 required submissions for each stage of design and was also expected to develop from design project 4 that students would have completed as the previous year as part of the same design group, with the same industrial sponsor. Students were assessed through group submissions (project report; modelling work; posters; and presentation) and individual components (viva voce; peer assessment; and project advisor performance).

Morgan (2017) observed a total of 12 design sessions of the team, comprised of Clara, Jim, Simon and Toby (pseudonyms), across the 20 weeks in which the designs took place. In addition, other named individuals were Hugo (university project supervisor), George (industrial liaison officer), and Anna (representative of commercial sponsor Design Co). On occasion students engaged with others including Aidan (from Bristol traffic control centre); Mitch (university modelling expert); and Ivan (Geography Postgraduate).

6.4.2 Reconciling Conflicting Design Expectations

As mentioned in the context of DP5, the project involved direct engagement with a commercial (or industrial) sponsor - the same sponsor from the participant's fourth-year project which was focused on the design of a city-bike scheme. Among the design studies considered for secondary data analysis, DP5 was unique in this regard - none of the other design projects involved direct involvement of a commercial/industrial sponsor in relation to the projects. While CE design did include industrial involvement for the purpose of assessing students' hazard and operability (HAZOP) study, this was a focused and distinct component of the CE design project which had limited impact on the design as a whole. This feature is emphasised in the documentation for DP5:

> Develop a design requirements specification that captures all of the functional design requirements, as well as the economic, social and environmental constraints. This must account for the needs of both the project sponsor and all other stakeholders in the product/system. (p. 106)

This core assumption about the DP5 was returned to regularly throughout the students design and emerged immediately at the onset of design at the students' first meeting with university supervisors, George and Hugo, and Anna from Design Co. Anna states that "the nub of it is to 'Aggregate data and use it to create wider economic value' and … to 'Create an architecture to manage this data to create value for the city'" (p. 105.). In response Clara, one of the members of the DP5 student group, confirms that they want to "[a]lign themselves more with Design Co.'s current situation" (p. 105). At these initial scoping stages of design, and following this interaction, the academic context is invoked considerably, which set the tone for the recurrent theme of misalignment in the goals and requirements of professional and educational design. Both Hugo and George protested to the direction of the project proposed. Hugo suggested that the students "'[focus] on something more specific…' a possible systems project… a black box" (p. 106), however George even opposes this suggestion stating that "'if you treat the device as a black box, what are you actually going to DO (for the project)'?" (p. 106). This demonstrates that even in the educational context, there may exist competing expectations and perspectives around design.

In CE design, there is, conceptually, a similarity to the above type of interaction. This can be found in the subjective constraints of supervisors and how students inform their design practices in response to supervisory suggestions. Students focused their efforts to ensure they addressed aspects that were deemed to be important to their supervisor. However, the design brief may also be ambiguous and supervisory advice may contradict statements found in the design brief documentation. Interview participants of the CE design to varying degrees reported dissatisfaction with the lack of conformity across supervisors and their guidance around constraints. Although the context for CE design was bound to the educational setting and not a professional one, it demonstrates that factors and constraints from the educational context can still conflict or, to employ Morgan's (2017) terminology, result in "paradoxes in design discourses".

During the aforementioned first DP5 session, George (industrial liaison adviser) also alluded to the educational expectation that DP5 students should link to their fourth year design project. Morgan reports that he was "anxious that they [were] throwing most of their 4th year stuff away" (p. 106) and he was "concerned that [they] work in such a way that [they] get a very high mark… keeping Design Co. on-side [was] a secondary concern." (p. 107) These excerpts offer significant insight into the possible 'paradoxes' that emerge with design in an educational setting. In such projects involving commercial partners, commercial successes and priorities may not align with the educational equivalent. Reconciling the two is the primary focus for DP5 students throughout, although perhaps due to the ambiguity of their design, Morgan concludes that the DP5 students "[a]ligned themselves… closely to the *commercial sponsor* discourse and neglected the *university* discourse… and ultimately failed to resolve [the central paradox]"

(p. 150). Notwithstanding, the DP5 students repeatedly mentioned the desire to perform well academically.

> They seem reluctant to pursue their 4th year project any further. George says “At the end of the day I don’t run your project, Hugo doesn’t run your project, Anna doesn’t. You’ve got to decide what you’re going to do”. Jim points out …“but you do mark our project”. Everybody laughs. (p. 106)

> They discuss what their objectives are. Toby says, “Getting a high first”, Clara “Beating everyone else’s firsts”…and “Ideally something that would be applicable to our jobs next year…. I know Jim accused me of making this a Design Co. job application!” Toby says, “Use work that some of us have done last year”… Simon suggests that making themselves “invaluable” to Design Co. is a good objective…if they want a job. But Jim points out that this could be in conflict with their main objective of getting ‘firsts’. (pp. 109 - 110)

With George’s assertion that the students decide themselves - advice that is oft repeated by advisers in CE design - Jim’s response was to invoke the academic conditions to bring the design problem into context. This excerpt demonstrates the persistence of the academic context - that students are ultimately being assessed as part of an academic exercise which may preclude success in professional design, even though commercial design holds connotations of “authenticity” - as demonstrated by Simon’s comments about Design Co potentially offering a job based on success in the project. Despite this awareness of the academic context of the design project, DP5 students subsequently prioritised the commercial context of design over the educational requirements but the tension persisted throughout their subsequent meetings.

> Jim suggests that “Rather than trying to put this report together for George and Hugo, we’re just putting it together and making sure that we’ve got what we need… using the two weeks productively, rather than using two weeks to try and fudge something together so that we can pass this ‘pass or fail’.” They discuss that the preliminary report is just to ensure that all the groups are actually following a process and focusing on a sensible project. They agree that they don’t need to worry about the precise details. (p. 114)

> They define Design Co. as being their customer. Toby says they need to understand Design Co. better, that Design Co. are their major stakeholder and that they’re doing a case study defining the requirements from Design Co’s point of view. (p. 115)

The above excerpts point to somewhat of a turning point for DP5 students for whom the educational requirements for DP5 were afforded less import in relation to their decision making with respect to their design solutions. A critical step in the design problem formation for DP5 students was to determine who was the customer - Design Co., in their circumstance. For CE the analysis used the term ‘client’ which could be interchangeable for ‘customer’ described here. For DP5 students, there was a distinction between the design customer/stakeholder and the academic evaluator, and hence the contexts of design, or discourses in Morgan’s (2017) terms, were more differentiated. As a result, this disconnect gave rise to a more extreme “paradox”, or conflict in requirements. In contrast, in the CE design study and the DP1 study, the academic supervisors subsumed both roles and hence there was less conflict in this regard.

6.4.3 Practical Demoing of Design

Another reported concern of DP5 students centred around the need for practical demonstration of their design, both as a requirement of the educational project and also to their commercial supervisor. This is emphasised in conversations early-on between the DP5 students themselves and also with both university and commercial advisers too, who emphasised the need to define and produce a clear design deliverable.

> Hugo [supervisor] suggests “Focusing on something more specific, something they could track…” He’s worried it is still too broad. They need a concept by week six of the project. (p. 106)
>
> Simon says “I’m not exactly sure if this is too broad. I’m slightly concerned that in 6 months we’ll end up with no real deliverable”. (p. 106)

A concern both Hugo and Simon share is the possibility that a broad scope in their design may result in no tangible output. This demonstrates that students in DP5 were required to adapt the scope of the project in order to ensure that they could produce a practical design demonstration. In the case of both DP1 and CE design, since the scope, in general was well defined there was less responsibility on the students to define this for themselves. Nevertheless in the CE design, students did try to manipulate the scope of the design where there was ambiguity in the design brief. For example, during detailed design many students negotiated for approval on whether all unit operations needed to be designed, or whether they could decide to prioritise certain units.

Another aspect which informed the scope and requirements for the DP5 students were the practices of other students who had taken or were taking DP5.

> Hugo talks about what a previous student group did, as an example of what can be done, George recalls another. (p.108)

The supervisors used their experiences of DP5 to outline examples of projects that had been successful in the past as a way of guiding the DP5 students with respect to their own design problem definition. Later, at a meeting with the group, Jim cites an example of another group who were undertaking DP5 alongside them.

> Jim talks about one of the other student groups doing a robot project, which is very technical. He suggests they need to find some technical aspect of their project to focus on, to come out at the end “with something really concrete”. (p. 111)

Jim draws out features of the other groups’ design - specifically that their design included a significant “technical aspect” which would result in a “concrete” output, and immediately contrasts this with their own design problem definition at the time:

> Jim “The problem with all these problems is that all the solutions require us to look at, like policy… it means we have to put things in our report which are like these ‘ideas’ things, rather than the engineering side”. (p. 111)

By comparing to a peer group, Jim gets to the problematic aspect of how they have been approaching their design problem definition. This demonstrates how peers’ approaches aid understanding of conventions as students are trying to balance the academic conventions of design problems with the reality of the design problem. Even though students stress the importance of problem definition here, this is immediately associated with design solutions - which are not appropriately “technical” to fulfil the educational design requirements. These students were attempting to define a problem, meanwhile ensuring that the resulting solution “fits” the expectations of educational design. Similarly, CE design study participants also used the normative approaches of peers as an inference for quality and expectations around design requirements. Opposing the dominant approaches to design was uncomfortable for students, such as Cain Bruce’s feeling of disadvantaging himself by opting for an original design.

The struggle that the DP5 students faced, to concretise their otherwise abstract design problem, carried through the entirety of their project. At a later stage, the students review their progress with their supervisor, Hugo, who confirms the necessary component of a practical demonstration.

> The group start the session by discussing objectives, deliverables and requirements. Hugo talks about needing a practical demonstration of their project. He says without it their project will be too “high level” and “theoretical” … but “unproven”… Without having some kind of demo it would be difficult to convince all stakeholders…” (pp. 118 - 119)

Hugo explicitly stated the expectations of design - namely, the academic requirement of a ‘practical demonstration’. This appears to be a form of supervisory intervention - Hugo recognised that the group’s direction of design may inhibit the main requirement and hence makes this clear to students. This is akin to CE supervisors cautioning students about complexity of detailed design section - if the unit(s) did not offer sufficient opportunity to demonstrate knowledge and application of chemical engineering principles, it was deemed necessary for supervisors to intervene. In this sense, the supervisors were the 'enforcers' of the academic design constraints. Although Hugo cautioned students, overall he provided little direction for students, discussed later. Due to the lack of clarity around what the main design deliverable was, even the DP5 commercial sponsor remained confused about the the aims of the project.

> "Anna asks the group what the "end thing" is that they're going to come up with. Clara jokes "I've absolutely no idea!" The report is the main deliverable, she says. It's a kind of 'how to' guide." (Page 128)

The inability for the students to clearly define the requirements for their design led to significant confusion for the stakeholders of the project itself, but also the students between themselves. Contrast this to CE design, where students have a distinct individual phase, where the wider process is fixed to some extent. The DP5 students under investigation were not subject to the same "fixation" of their design, so the design solution remained modifiable even until late into DP5.

> Toby "The whole point of collecting data is to show we can do things in reality, like our actual case, so then we put in real data that we've collected into GIS… it's just to say you've done it". …. Simon "OK, so it's purely for a demonstration of the data being able to be imported"… Simon "We're not really looking to use these cycles for information". They discuss… the point is they're just demonstrating the possibilities. Simon keeps worrying that they're going to try to use the data to draw conclusions. He needs reminding that it's just for demonstration. (p. 132)

The above excerpt revealed that there was varying degrees of understanding of the design requirements and deliverables of the project. This interaction occurs relatively late on in the project, suggesting that the design group is somewhat fragmented. Although there is a requirement of a 'practical demonstration' mentioned earlier, the project remains abstract and process orientated, further contributing to the degree of ambiguity in understanding of the design requirements at such a late stage.

In the excerpts, Toby from the DP5 study, demonstrated the most confidence in understanding the requirements and deliverables of the project, and was "worried they're doing things the wrong way round i.e. tool/process. He thinks they need to go through the process and flag up any bits that may have been missed, any tools that they need to develop" (p. 132). A consequence of the lack of clarity surrounding the main deliverable for the design project for DP5, is the inclusion of elements for the sake of meeting the educational design requirements for a practical demonstration.

> "Simon says "I think all these tools that we've used to actually do the project kind of… I think they might actually come out quite well, because it's…" Jim "It'll look

> good as well, stick ’em in our report… it’s a whole process, a design process”. (p. 133)

Since they were unable to concretely define the deliverables themselves, the approach was to address the educational requirement superficially, further impacting students ability to define, and hence, practically demonstrate the design deliverable. In part, the inability to make the design fit with how students perceived the norms and expectations around DP5. In Morgan’s (2017) final observation of the DP5 student, the students met with George (university industrial liaison officer) and in response to what will be included as part of their presentation, Toby responds:

> “The thing about this project… we knew what the problem was, we’re having to develop this process… we haven’t been requested any deliverables. We can make predictions right now what will be in our presentation, but that doesn’t mean it’ll be there. Because we don’t really have any requested deliverables… we’re working through this process. It’s really, really likely there’ll be some modelling like this… it’s a tool box, but we can’t say what the tools will be until we develop them, so we can’t say what we’ll be presenting.” (p. 137)

This lack of clarity around meeting the design requirements with respect to practical demonstration persisted throughout Morgan’s (2017) of the DP5 students. Morgan (2017), states that the following in her analysis of DP5 students’ behaviours with respect their inability with design.

> The fifth-year group were more problem-focused, and actively seemed to avoid solution-conjecture. During session 2, I noted in my field notes that “They keep heading towards discussing solutions but then check themselves, as if that’s wrong, and then try to think of more problems instead. They seem a bit stuck and bogged down in problem-definition.” … This problem-focused behaviour seems related to the tendency of the fifth-year, group toward convention based (rule-based) thinking. Unable to adapt to the particularity of the design situation, instead seeking to apply rules and methods, or to try and quantify things that are not really quantifiable. (p. 153)

While the above analysis captured the tendency for the students to avoid solution-conjecture, which Morgan (2017) contrasted with the DP1’s students “solution-focused design behaviour” (p.152), there was little emphasis placed on conditions of design that may have impacted students behaviours.

It is likely that the peculiarities of each project impacted the students’ behaviours. DP1 is much more structured; with a clear design specification (i.e. the design problem is relatively well defined); focuses on a physical product as the main deliverable; and has a relatively congruent, or at least dominant, design context (i.e. there was no competing commercial stakeholder as there was for DP5). In DP1, we find that the 'physicality' of their problem - that they must design a vending machine for plastic cups - facilitates students focus on demoing a "functional" design. These factors are likely to enable solution-focused behaviours that Morgan observed in the DP1 study participants. While CE design lacked the aspect of a physical design, the focus of the design was relatively clear in each phase of design.

6.4.4 Competency Constraints

At their first meeting with their project supervisor (Hugo) and industrial liaison officer (George) and their commercial sponsor (Anna from Design Co), in response to Anna's suggestion of a data-centred project, the following responses were made in relation to the suggestion.

> George reminds the students that they are "Design engineers, not computer scientists" and their project should be the "Nuts and bolts" level of design. (p.106)
>
> Simon points out they don't have enough know-how to design the actual gadget itself. (p. 106)

Here since the design requirements are vaguer than in CE design, we observe that technical expertise was considered a critical component for scoping out the design problem. In CE much of the scope is dictated since the problem, although abstract as it relates to a process, is more "concretely" defined (e.g. design a plant that produces X tonnes per year of Y in Z), where X, Y and Z were all provided specifications. In contrast, in this study the formulation is even more vague where the design requirements need to be developed (e.g. determine the design requirements for A, determine possibilities and finalise a design) where the only fixed elements for the individual group was the stakeholders of the design.

For DP1, the design requirements and specifications were even more concrete than that of the CE design and the result is a much more iterative approach to the issues around technical functionality. DP1 students were assisted through technical aspects as they also had walkthroughs of technical aspects with technicians (e.g. demonstrations of actuation/sensors).

Among the DP5 students, Toby who appeared to have the least confusion about the aims of the project was also demonstrated repeated concerns around "competency constraints" with respect to the direction the project was taking.

> Toby is worried that this problem could result in an overly technical project that he wouldn't understand. (p. 112)
>
> Toby raises a concern… "I do understand why we need to collect data, but my big concern is that we could end up spending a lot of time and not end up gathering that much data, and then not having that much direct… value from the project". (p. 119)

> “Do you feel like our project really requires an economist or statistician… the amount of data we’re dealing with is like… (!)” Toby says, “This is true… might be one of the things we need to protect ourselves against”. (Page 125)

While design must be significantly ‘technical’ it cannot be too technically advanced that students find themselves lacking the competencies to engage with the design problem and solution. This relates to notions of competencies and how students must strategise for an achievable solution. Toby came back to this as a guiding principle repeatedly in the DP5 project. In addition, among students concerns is the possibility of wasted or “sunk” efforts, as indicated by Toby. The response from students was to adapt their designs to ensure that they minimise the risks associated with design decisions. Toby and the DP5 students engaged in “protecting” themselves from technical inaptitutde by primarily altering the design problem/solution to fit their competencies. Students in DP1, such as Joe, demonstrated proclivity to “de-risk” the design to prevent possible issues downstream in the design process.

For CE design, students begin with the assumption that the brief is achievable and in line with their expertise, although later this becomes contentious with students becoming aware of gaps in their knowledge, specifically around individual detailed design (e.g. Iona Mitchell’s difficulties with batch processes and Will Ross’s account of his friend being unable to progress with crystallisation). Nevertheless, students strategised to ensure that they shared a design space with friends and peers that they could work with such as Aman Chowdhury who had agreed beforehand with his friends that they would “pick” the same detailed design in order to pool competencies.

Competency constraints was a returning aspect of DP5 students practices, especially given the degree to which their project was open-ended, but also relates to CE design and DP1.

6.4.5 Compartmentalising Design

The DP5 documentation provided students guidance on various aspects related to the design. One such aspect was that students had “to outline roles and responsibilities within the group” (p. 113). In response to this, “Clara suggests they start doing parts of the preliminary report individually” (p. 114). When formalising roles about the design that the student approach to responsibilities focused on individual roles:

> The group decide whether to do the design together or individually, they agree maybe one or two people would be enough… so Jim and Toby should sort out the sensors stuff together. (p. 119)
>
> “Simon says, “So we’ve done the definitions of the individual blocks that we’ve been looking at, now we want to understand…” He isn’t sure how to say what he means.

> He asks the others, “What do we actually need to be doing now?” Jim says, “An integration plan”. They seem quite confused by their own project.” (Page 124)

There is some grouping in the first excerpt, but largely the group worked on individual “blocks” as evidenced in the second excerpt. This is further demonstrated in the students’ approach when they updated their project supervisors and commercial sponsors which involved explanations of their own individual contributions.

> The next phase is integrating those modules, then applying it to Bristol. Jim has been defining the generic ‘city’, as part of the ‘Metropolis’ module…. Simon explains his area of work, that he used work from last year plus new literature review to define a typical bike scheme. … Toby then talks about his area of research, ‘data’. How they’ve been cycling at rush hour and collecting data to demonstrate the possibilities and pitfalls in a city like Bristol…. Clara explains that she’s been looking at the application to Bristol as a case study, building on her 4th year work. She looked at Design Co.’s future cities demonstrator document. (pp. 126 - 128)

Although, allocations to individuals is expected from the documentation the students generally engaged in a compartmentalisation-based approach to the individual roles and responsibilities, working largely in silos.This mirrors what is mandatory in CE design - the formalisation of “individual detailed design”, where compartmentalisation is emphasised from the IChemE’s accrediation requirements.

Although, the DP5 students tried to update one another through Morgan’s (2017) observed design sessions, there was a general theme of the students “not being on the same page” as described prior. Morgan (2017) does not provide further information with regard to the students design practices around communication - only what can be inferred from conversations during the observed sessions. The focus of the design sessions tended to be updating one another on individual updates - which may suggest that students were perhaps not as communicative in-between sessions - despite three of the students being flatmates.

Another possible indicator of students approaches was the variability of the setting of the observations. Morgan observed DP5 students in various settings ranging from Design Co.’s offices; homes of the students on two occasions; in Bristol traffic control centre; to Vice Chancellor’s room. The majority of the observations included in the study, 7 in total, took place in two design studios at the university (Studio 1.59 and Studio 1.69). It was not clear whether the observed sessions were “in full”, that is whether the meetings ran prior to, or beyond, Morgan’s observations, or whether students carried on working in close proximity in general. One possible interpretation of the presented data would suggest that the students did not necessarily work in close proximity, as many CE design students chose to do. This may contribute to a possible understanding of why students on DP5 were not fully aligned on their designs, although this cannot be conclusively stated.

Another factor to consider in relation to the differences in DP5 and the CE design is the duration for which these run.

> It is now January and the students are back from the Christmas and New Year break, at the start of a new teaching block. They are meeting again for the first time this year, just briefly, in Queens, in the same studio where they met Hugo in the previous session, studio 1.60. They're taking it in turns to explain what project work they've done during the holidays. (p. 120)

CE design covers a single semester, which contrasts with DP5 which took place over an entire academic year. Students in CE were working with greater restrictions, or constraints, with respect to project duration and we can then classify CE design as a project with relatively greater 'intensity' than DP5. CE students must attend weekly meetings with their group and supervisors throughout the projects and in the individual phase too, however in the group phase there is much closer working that takes place (partly due to the shared assessment). Since meetings and catch-ups take place more frequently, social loafing would be expected to occur less, but nevertheless still took place. Morgan does not indicate whether this was the case for the DP5 students and there appeared to be progress and contributions from all members. A possible factor that may have discouraged social loafing was that three of the DP5 students were flatmates and hence there was a social deterrent for social loafing.

6.4.6 Seeking Supervisory Affirmation

From a qualitative perspective, there was a particular session which offered rich insight into the supervisory relationship DP5 students had with their project supervisor, Hugo. Session 5, which Morgan (2017) subtitles as "Seeking affirmation" was a relatively short meeting which took place 6 weeks after the initial kick-off meeting. During this meeting the DP5 group spend most of the time updating Hugo and actively attempting to draw out feedback, which proves difficult. Several excerpts are provided below that capture the challenge:

> Jim says they've made changes to their preliminary report, they've reduced their list of objectives significantly, to simplify things. Hugo looks at them and says, "That's fine". (p. 118)

> Jim says to Hugo, "So that's the report. So it would add a lot to have done the actual physical modelling and got the data". Jim waits for Hugo's response, but Hugo doesn't say anything. Jim continues "Sorry, that was just a kind of overview… just so you're aware". Hugo says "Mmm OK" and nods. (p. 118)

> There is a very apathetic feel to this meeting, like the group are waiting for more information or direction from Hugo… but he isn't providing it. He sits back. A lot of strained silences. (p. 119)

> Clara asks Hugo "Do you think this (the project) is going in the right direction?" Hugo nods and says, "Yeah absolutely" but he doesn't seem sure." (p. 120)

Hugo, the supervisor, appears to repeatedly withhold feedback, or affirmation as described by Morgan. The supervisory approach described here was comparable to some reports from the CE design study. For example, Dr Ohlson, Frank Hill's advisor, was reluctant to provide explicit feedback or responses to students' questions. Ohlson is mentioned by participants other than Frank Hill such as Will Ross or Cameron Hooper, who he was not supervisor for, suggesting that individuals develop reputations for their reserved approach to interactions among the cohort.

In the last of the excerpts above, Clara seeks explicit affirmation of their progress - possibly attributing to Morgan's (2017) choice for the title of the session. Such questions function to provide students with confidence in their progress and decisions. The educational evaluator is the primary source for such verification. With regard to the notion of 'the design problem', the evaluator's comments contribute to concretisation of the otherwise ambiguous design space. By obtaining affirmation from supervisors students are able to fix/solidify their assumptions and move forward with design. This highlights a critical component of design supervisor interaction in an educational context, without which students' conceptions of design decisions remain tentative. Morgan mentions the seeming lack of resolve in the supervisor's affirmation which is likely to dampen the concretisation of their design solution.

It can be posited that academic supervisors lie on a spectrum defined by the two contexts which inform design projects. Supervisors with an educational-focus may be reluctant to provide direct feedback and place an emphasis on educational evaluation, ultimately creating a clear distinction/separation of the adviser and group. Design-focused advisers can be characterised by their willingness to provide feedback and guidance more often; prioritisation of design aims; and a participatory relationship in the design. The former takes the primary role of an educational evaluator and the latter, a design guide. In the DP5 study, from the above excerpts, Hugo appeared to align closer to educational context, hence his detached interactions with the students. This contrasts with George, the university industrial liaison officer, who offered significantly more guidance and feedback on their progress. From a separate meeting Morgan (2017) recounts:

> Clara "Is there anything that's jumping out at you that you think would be…" George "Well I'll be incredibly personal for a minute…This is one of the biggest frustrations I have with this job, that you 5th year students, you come back with things that knock the socks off what most people would have done, then you all disappear."… George says "OK good… I'm delighted with how you're getting on". (p. 137)

It is likely that the responsibility of evaluation will influence the degree to which supervisors align themselves to each role. Hugo is partially responsible for assessment - the DP5 documentation indicates that their individual assessment factors in the project adviser's assessment (as well as peer-review). George, however, it appears had no influence on the student's assessment. Morgan (2017) does suggest that the students were not fully aware of who assessed their project reports: "Is it Hugo? No, they think it's George (they're wrong)…" (p. 134)

It is important that the students were not aware entirely of who marked their reports. This created a level of ambiguity of the design problem in terms of evaluation which comes from the educational context. This, however, is clear among students in CE, the supervisor(s) act as markers and so supervisory comments have a significant impact on students' perceptions of design requirements. Frank Hill, who experienced difficulties in drawing out design requirements from his individual design phase supervisor, instead pooled information from peers in different groups with different supervisors. In the interview, Frank suggests that there is some, at least weak, belief that the evaluation criteria are objective, but implied that he was aware that this was unlikely to be true.

Later in the design, the DP5 student appeared to have a clearer idea on the responsibilities of marking but were still discouraged from seeking feedback based on the prior interactions they have had with Hugo.

> They wonder should they ask Hugo if they need to collect more data. Simon says he's not sure they should ask Hugo about additional data collection… "The thing I'd be worried about is, if we ask Hugo he'll probably say yes, then when we ask him why… and you get some muffled response that none of really understand… but then we're kind of forced to… it forces our hand into doing it, without it being a benefit". Clara agrees, "Yeah". Toby "Yeah I can see that point. I kind of think he's like our project advisor, so we don't ever have to do what he says, but its stuff like this that we try and get advice on. I think the policy of not asking him things because we'll feel we're tied in… but I do see your point". (p. 134)

CE students engaged in similar behaviour. Student withheld asking questions or clarification in case they were obliged to recommendations that arose. Such an approach helps students in 'managing supervisory expectations'. Seeking supervisory feedback is then somewhat of a double-edged sword for students. On one hand, students are able to obtain concrete feedback and affirmation which addresses ambiguity in design. On the other, students may inadvertently create more work for themselves and ultimately introduce more, or different, ambiguity.

6.5 Goncher (2012) Designing Sustainable Engineering Products (DSEP)

The following section covers the study by Goncher (2012). The analysis involves significant integration of both the CE design study and also incorporates connections to Morgan's (2017) study.

6.5.1 Context

Goncher (2012) studied teams of first-year engineering students undertaking an eight-week long project as part of an engineering design course in Virginia Polytechnic Institute and State University, United States, in the 2010 Spring semester. Students undertaking DSEP did so as part of the ENGR 1234 Engineering Exploration which had an associated 4 ECTS credits, alongside other courses up to a total of 36 ECTS credits. In addition to the project itself, students also participated in workshops that ran as part of ENGR 1234 which were not observed. These workshops were delivered by a workshop leader who was also responsible for grading the assignments produced.

The central design objective was to "develop a Promotional Innovation that publicizes awareness of a renewable energy source" (p. 37). Similar to the study of DP1 studies completed by Morgan (2017), the DSEP students explored by Goncher (2012) were required to build a physical prototype of their design and the DSEP documentation incorporates this as one of its design requirements, that the design had to be functional and "should showcase the creation of energy from a renewable source, not just as a conceptual model, but as a physical implementation" (p. 169). Another shared similarity for both studies was the inclusion of a budgetary constraint, in this case of $20. With respect to assessment and feedback, DSEP had more frequently graded submissions throughout the design process, whereas DP1 in the study by Morgan included weekly activities for completion – however the project itself was not assessed formally until the end.

Table 6.1 Teams, Pseudonyms and Finalised Designs for Goncher's Study of Designing Sustainable Engineering Products (DSEP)

Team	Members (Psuedonyms)	Final Proposed Design
Team 1A	Eddie, Jason, Cory and Kelly	Solar Canopy
Team 2A	Kevin, Coleman, Jim and Gary	Hydro-powered Bridge Light
Team 3A	Cullen, Andy, Brett and Ian	Solar Cooker
Team 4A	Craig, Channing, Neal and Cody	Hydro-powered Urinal

For the design project, Designing Sustainable Engineering Products (DSEP), students worked in groups of four that were either self-selected or randomly assigned. Goncher (2012) followed four teams who all completed the project and their pseudonyms shown in .

According to Goncher (2012), the instructor arranged teams from the pool who volunteered for the study (as opposed to selecting teams then obtaining consent for study). All named individuals in the following excerpts were the DSEP students participating in the study.

6.5.2 Balancing Classes

Unique among the studies, Goncher (2012) highlights that across the groups studied, students commitments to other courses significantly impacted their effort and approach towards the DSEP assignments and course as a whole.

> Kelly: “Are you writing yours now?” Jason: “Yeah! I got to get this thing done; I got a lot to do.” (p. 60)
>
> Brett: “Okay, so where’s…I’m trying to get this done so I can go back to studying for Physics. I haven’t started yet. I’ve been trying to do the quizzes and stuff and it’s not happening. I always have to look at my notes and stuff.” … Cullen: “I’ll do that just so we can, once we get there we can pretty much… pretty much just be like, think of 5 ideas and let’s leave. (p. 96)
>
> Channing: “Because it’s a ridiculous amount of work for two credit hours.” Craig: “It’s kind of frustrating.” … Neal: “I’ve definitely heard this class is meant to weed people out.” Craig: “I thought it was going to be extremely hard, but it’s just a bunch of tedious stuff.” (pp. 130 -131)

Goncher explains that it was a “common theme across teams where the team met to work on DSEP artifacts but also used this time to work on other assignments, going back and forth between work related to and not related to the DSEP” (p. 121). It can be inferred from the excerpts above that the students approached the DSEP as simply another course that they needed to pass.

Balancing other commitments was generally absent from the data for CE design, since CE design was the only educational commitment for most CE students while it was running, hence its attributed importance. The only exception among interview participants was Emelia Emese, who because of her status as an Applied Chemistry and Chemical Engineering (ACCE) was required to take additional chemistry classes in tandem. These classes impacted how much time and attention Emelia was able to offer the CE design. Not only did this impact her design activities, but as mentioned in the previous chapter, it also negatively impacted how she viewed the relationship she had with her group compared to the other member’s relationships to one another.

This finding around significant competing workload demands for DSEP students was relatively unique across the studies under consideration. This was perhaps due to the relatively low credit worth overall of the DSEP and that the project itself contributing only 10% of the students' overall grades compared to the wider programme. This contrasts with the CE design and Morgan's (2017) study of DP5 students. Interestingly, for Morgan's (2017) DP1 study which shared significant overlap in features with Goncher's (2012) DSEP study, such behaviours were not reported. This may be attributed to the limitations of a single, relatively committed group being the subject of Morgan's (2017) study.

6.5.3 Focusing on Function

Across all teams investigated by Goncher, student groups emphasised the importance of a functional design - that is one that would result in a functioning prototype.

> By constraining their search using the parameters related to functionality and applicability, [Team 1A] did not seriously consider ideas outside of their initial design concept. The … team members perceived geothermal as a renewable energy source for their final design; they ultimately chose solar energy based on their assumptions of how solar energy could be applied to their design. (p. 73)

> Overall, Team 2A constrained their search by project parameters, i.e. functional and possible/ applicable … Making a working model was a salient factor throughout the design process and suggestions related to the development of the final design were usually questioned by asking, "but how would that work?" (p. 78)

A similar early fixation was demonstrated in general with students of CE design. This was in part to do with students' approach and understanding of design in a CE context. Functionality was more difficult to assess earlier on in design stages, and so students in CE for the design of wider processes relied significantly on 'existing models' of processes (e.g. patents, models found in papers etc). These models acted as indicators of functionality and ultimately restricted the design space.

> "So, I think that was quite hard. Because I think for this project, it was quite – there was only two ways to do it, but then one way seemed a lot more prominent than the other. And there wasn't really any information about anything else, so everyone was basically using the same information." *- Natasha Douglas*

The DSEP students also constrained their design options relatively early on but focused on the criteria of functionality.

> And the fact that we actually had to build a prototype for it restricted what we could do (Gary, Focus Group Interview). (p. 89)

For individual detailed design, CE students were somewhat more engaged with functionality of their design as they became more aware of the complexities emerging from previous decisions made around models. Depending on the prevalence of standardised design methods and data available for a given unit operation, students attempted to resolve the challenge of functionality in their design using mathematical methods or computer simulation (e.g. Aspen).

> It's very easy to get into a hole where are you are looking for one figure and you just can't do it and you're trying to run it through Aspen to get it to spit a figure out and it's not coming out properly, and you're trying to go through every data that you've ever heard of trying to find stuff. *- Cain Bruce*

Overall, this resulted in a perceived limited and constrained design space. It can be hypothesised that functional design parameters remain somewhat relevant but to lesser degree where physical prototypes are not explicitly required at least in the earlier stages of design. This is evidenced in Morgan's (2017) DP5 study, whose students fluctuated between process and a physical demonstration - "without having some kind of demo it would be difficult to convince all stakeholders" (p. 119) and the CE design which explicitly required the design of a hypothetical, abstract process. This differs from Morgan's (2017) DP1 students, who spent a significant amount of time considering many different options, but nevertheless iteratively engaged with how the design would function before making a decision, including considerations around costs.

6.5.4 Deciding based on Know-how

Linked to the deciding factor of a design being functional was also whether a design could function given students' awareness of their technical know-how, as outlined by members of Team 4A.

> Channing: "Probably, because I would probably know a lot more by that point. We didn't really know much going into this. We just, we didn't know much of a mechanical basis, we just took what little we knew and built it." Craig: "I'm sure the creative part of it would be a lot better, and the functionality of it would be a lot better too for sure, because we would know a lot more information on what we're doing instead of going from research on the internet. We would actually have a background in something that deals with it…" (p. 127)

Goncher (2012) explains that Team 4A members "were taking engineering-related courses… however, they did not perceive the material from those courses as applicable to their design or design approach" (p. 127). This aspect of pre-design education and topics being irrelevant to design was thematically consistent with those findings from the CE design study as well.

Some students reported that they felt that even their precursor design class was not comparable to the design experience proper.

> But I feel like I've never done a design project before fourth-year. - *Natasha Douglas*

For example, students, such as Iona Mithcell, found designing for batch operation for processes to be particularly difficult as primarily they had been taught about continuous processes through their programme. Some students, such as Iona Mitchell, opted to modify their process with a counter-intuitive approach, which allowed them to operate their batch process continuously.

> I sat for a week and try to work out how to design a batch distillation column – and eventually I was like… "I don't know how to do this!" So, I just put a storage tank at either side and just made it continuous. But that's not a batch process… For a batch distillation column, it all goes into still and it will evaporate off, but it isn't steady state and you don't know how much you need… And I was just literally like "I can't do this!" - *Iona Mitchell*

Despite Iona proceeding with her design under this assumption, she understood that the overall design was incongruent with earlier design decisions. In response, Iona outlines how she coped with detailed design by distorting aspects to make it workable according to her technical know-how. This aspect of not being able to relate their decision to course topics may have contributed to students over-reliance on models as students lacked the technical know-how to independently arrive at design solutions. Lack of technical understanding may also inform CE design students adopting strategies around selection of unit operations for detailed design. In order to maximize technical support around design, students may favour designs that maximise conceptual overlap with friends and similarly tasked peers.

Making decisions on design based on technical abilities is evident in Morgan's (2017) DP1 and DP5 studies. In the latter, as early as the initial design meeting with the commercial sponsor both the university liaison officer and the students themselves rule out design possibilities based on lack of domain expertise - "Design engineers, not computer scientists" (p. 106) and know-how.

6.5.5 Superficial Conforming for Design Submissions

As demonstrated in the CE design and Morgan's (2017) DP1 study, student design practices situated in the context of an educational setting are significantly impacted by the documentation related to requirements and evaluation. Goncher (2012) reiterates this, informing that students "relied heavily on the DSEP document to frame how they approached and completed DSEP design activities" (p. 56). This reliance on documentation coupled with students balancing work, may explain the DSEP students' superficial treatment of various design aspects.

> Jim: "How we narrowed it down? Like, how did we find this was the best option? Just make it up." Kevin: "Alright let's make it up. It's like 1-2 paragraphs." (p. 81)

> Eddie: "Can you send me the list of ideas so I can just make up some random…how we narrowed it down." Kelly: "Yeah. I'll send it to everyone." (p. 72)

> Brett: "All right, so you'll do the define the problem." Andy: "The test and implement the solution." Brett: "All right, I'll start pulling shit out of my ass magically then." (p. 115)

> Andy: "You got it? Okay discussion. Time to make up some stuff." Cullen: "What did it [DSEP document] say? How effectively did you use brainstorming?" … Andy: "Yeah. We don't want to say we used Google because then she'll be like "oh… Yeah…"" (p. 114)

At times, students did not value the purpose of certain design requirements, an example is the interaction outlined between Eddie and Kelly. It can be noted that the response from the student was to superficially and retroactively address the design requirements. Students chose to meet the educational design requirements out of necessity with the understanding that these impacted the evaluation of their designs. In part, the purpose of retroactively engaging with design processes was also to conceal the actual approach taken and portray compliance with the design requirements for the DSEP. In some reports from Goncher (2012), owing to a lack of available time to do so, students went as far as fabricating entire design processes such as testing.

> Cullen: "Yeah [say] it was cloudy or something. It is cloudy. We intended on testing it this week but Mother Nature wasn't cooperating." Brett: "We tested it this week and it was too cloudy." … Brett: "Thank God. If anybody asks, we tested it but it was too cloudy to work. That's our story and we're sticking to it." (p. 116)

There was an implied understanding from Brett from Team 3A that such fabrication of design processes was unacceptable in the context and that they must actively resort to deception to meet the design requirements. Even aspects that were not explicitly related to a particular design phase, but related to the educational context of design such as peer assessment were reported as being dealt with a perfunctorily manner by some students of the DSEP. The following interaction Team 4A, suggests that superficial treatment of elements by copying their own earlier work with respect to peer-review involved an element of deception.

> Craig: "Do you think she cares if we copy and paste from our old evaluations?" Neal: "I'm sure if she found it she would care." Channing: "So just don't get caught." (p. 126)

This notion of "not getting caught" was implied as a strategy by Will Ross in the CE design study. In his case, this was an approach to overcome known deficiencies in his submitted design.

> I still feel guilty for the engineering simplifications I made. I used – I found data for a pilot experiment that were for a reactive distillation column, and I said "oh, this data is applicable for a well-mixed CSTR" and then they only gave the temperature for the thirteenth plate of a sixteen-plate column, and I said that's the temperature of operation. Which is the stupidest thing you can do, but I couldn't do anything else, I had to make some sort of choices, and I just did it. I dunno, in my report I didn't mention that it was transferrable. If they think that I think that's fine then I'm in trouble, if they don't notice, then it will be perfect, like if they don't read my references. But it's done now. [laughs] - *Will Ross*

6.5.6 Following Experienced Contacts

A factor which influenced students understanding of design in Goncher's (2012) study was information shared by students that had already completed the DSEP, such as roommates and friends.

> Andy: "Yeah, I think wind would be easy but it's also easy to screw up on." Brett: "Yeah, it's hard to make propellers." Andy: "That"s exactly what my friend did . They botched theirs…they messed up on stuff to use." (p. 98)

> Cullen: "My friend said he would give me all of them." Andy: "What?" Cullen: "My friend's giving me a few. He took it last semester. He said water-powered conveyor belt." Andy: "That would go well in lines with our water-powered elevator. (pp. 98 - 99)

Comparing with the CE design study these excerpts related to the notion of normative practices of sharing information and students developing a socially informed understanding of acceptable design behaviours based on connections with students from previous cohorts.

> We communicate with people in other year groups, my flatmate is in the year above. So when he was doing his project, I remember him struggling a lot and he was just doing one unit. And it was easier than our unit. But I remember thinking, "that's a lot of work!" - *Cain Bruce*

> Because, if you look at the reports- we've got reports from the years above. I presume the chemical engineering department aren't stupid enough to think we don't. - *Cameron Hooper*

These connections resulted in the distribution of reports submitted by students who had taken CE design before. Morgan's (2017) study of DP1 shares some relevance, however, with information about ‘last year’s winners’ being used to add a degree of validation of design decisions. Contributing to the importance of experiences and information of previous cohorts is the relevance of design problem across cohorts. Previous reports offered students with somewhat verified models for design, especially where there was significant overlap of the initial design problem and context, as was the case in CE design, Goncher’s (2012) DSEP and Morgan’s (2017) DP1. In the DP5 study conducted by Morgan, however we find no significant reference to previous cohorts, and this strengthens the claim that the importance attached to previous experiences depend on the degree of overlap of design context.

Goncher goes on to explain that Team 3A’s water-powered elevator idea was sourced from an existing model too.

> Their stereotype of the problem as an assignment rather than a design problem led them to rely on non-novel concepts, recycling other students’ ideas and making slight variations to existing ideas. The water-powered elevator was based on the DSEP document example from the brainstorming inventory, i.e. —wind-powered elevator. (p. 99)

The persistence of models and reliance on models is evidenced here. Students in DSEP Team 3A were reliant on existing designs without adequately assessing other possible options. Models have powerful influence on students thinking and limit design spaces without full consideration of alternatives. As such the ‘design framing’ that models offer can simultaneously develop students understanding of the design problem definition through example and restrict students design solutions without full exploration of the design problem space. In CE design, this was reported as being an aspect of the design brief which made it difficult to innovate. Natasha Douglas mentioned this explicitly in her interview.

> “So, I think that was quite hard. Because I think for this project, it was quite – there was only two ways to do it, but then one way seemed a lot more prominent than the other. And there wasn’t really any information about anything else, so everyone was basically using the same information.” - *Natasha Douglas*

Here Natasha refers to the design of the process which was an expected output from the initial group phase of CE design. Models, especially those from the literature, can be thought of as proofs of concepts. These offer students a form of verification and validation of a design, similar to that suggested by Goncher in relation to DSEP Team 3A selecting a ‘water-powered elevator’ found in the DSEP documentation. Further, they can, as suggested by Natasha, offer students information that will be necessary for subsequent individual detailed design. This demonstrates how strategic use of models were a method by which students efficiently reduce ambiguity around design but can lead to homogeneity in design solutions if design briefs were limited in scope. However, as students understanding of the design problem and solution spaces developed, they had to either reconcile differences, such as Iona Mitchell’s who did so due to limited know-how or abandon these models in light of new information as mentioned by Goncher (2012).

> For example, Team 1A had a rechargeable battery component (based on the roommate's previous project) in their design to improve the functionality, but ultimately abandoned this idea as the team progressed through the design process and began eliminating design requirements. (p. 63)

As students ideas related to design begin to mature and develop they may become aware of "unworkable" sources to support models (even those from social sources such as a member of a previous cohort). This suggests that technical understanding related to a particular design solution may compete with models and social consensus.

> So that's when you notice the things that didn't really make sense when you went into phase 2, like "oh, maybe that's not really correct." Because copying the patents – or when people give you past design projects, people start using them, but then I feel like people take them. Like, "oh, it must be right." But it's not actually right it all, and you're like "no, I don't think we can do that because that doesn't make any sense." - *Natasha Douglas*

We find this in the case of Cain Bruce, whose group realised that an aspect of a patent that many groups were using was not, in their view, technically viable. Such a decision led to a challenge to, and the disintegration of, the original social consensus.

In addition to the information shared, practices around design were also sourced from previous cohorts experiences which informed their decisions directly such as for Team 1A below.

> Cory: "My roommate used the same one for both. For the little…" Kelly: "Maybe we could buy all the parts but not put it together." Cory: "Yeah and just explain what it's going to be. 'Cause that's what he did. He didn't have it finished so they just took what they had and told what the finished thing would be." (p. 62)

> Ian: "Nah, you're straight. Someone from last semester, he told me, everyone just gives each other hundreds." (p. 100)

> Neal: "That's what…oh what's his name…when we were working on the homework…" Craig: "[student]" Neal: "He said they're [workshop leaders] graduate students; they actually have a life." Craig: "Yeah, [student] said don't even worry about this thing, just throw it together and go with it." Channing: "Who was that?" Craig: "He lives right next door to me in the dorm. But he's a second year and he did this." (p. 122)

Students were able to develop clarity around acceptable and normative practices in design. Ian from DSEP Team 3A highlighted how "intel" from a student from a prior cohort demonstrated how peer assessment was superficially managed and was used strategically by students - i.e. normatively giving each other full marks. In the example from Team 4A (Neal, Craig and Channing), students also obtain information regarding the evaluators to inform their decisions. This is similar to CE design, where students reported categorising report assessors as “good” (lenient) and “bad” (harsh) markers based on pre-design experiences as well as experiences of students from previous cohorts. Experienced contacts, then, are informants to the context of design that help students navigate around the design constraints in the educational setting. While this could aid student in learning from others’ past mistakes, the comparisons enabled students to deal with the design constraints superficially and underhandedly, as described in the following discussion.

6.5.7 Conforming to Design Requirements

A recurring theme among the teams that Goncher (2012) studied involved students superficial handling of design requirements, specifically around the $20 budgetary constraint. At times this superficial dealing with design constraints would also entail an element of deliberate deception, such as outlined in the excerpts from Team 1A and 4A below.

> Cory: “We just got to make sure we keep it under $20, which I don’t think will be a problem.”; “My roommate said too for stuff they…they bought stuff and theirs ended up being $21, or something. They just went on eBay and found the price and printed out a receipt.” … Jason: “This was 15[$]…the panel was 15[$]. This [wood used to make the model]… I’ll write up a statement from my dad’s business that it was $3 haha. And that gives us $2 to look for an LED.” (p. 75)

> Channing: “This is cost adjustment.” Cody: “[Workshop leader] doesn’t see this stuff.” Channing: “Dude, they want us to build something with $20 but they also want high quality. It’s like, come on now.” (p. 141)

This process of manipulating the presentation and reporting of design involved deliberately concealing aspects of design that were known to violate the constraints and therefore students demonstrated an apparent disregard for the educational design brief. In the case of Teams 1A and 4A, they went as far as fraudulently reporting costs and fabricating receipts. Team 1A’s Cory cites his roommate’s practices as grounds for justifying this behaviour evidencing how design practices of experienced students can also encourage undesirable behaviours. On the other hand, Team 4A’s Channing suggests that the design constraint for the budget was overly restrictive that the only practical option was to “adjust costs”. Team 4A reinforced that the cost was a main factor in their design decisions as mentioned in the following focus group excerpt:

> Craig: “Too bad we couldn‟t actually build something sweet. Like if the school gave us like, a 100 bucks or something.” … Channing: “Cost was definitely a major factor, not only for what type but after we had our brainstorming inventory ideas just

> making a final decision, cost was a major factor. You can"t do much with $20 haha."
> (p. 141)

Here an explicit constraint of the design problem directs Team 4's design decision making process. Ultimately, they restricted their considerations to designs that were possible given this explicit constraint. The CE design participants suggest that constraints around technical complexity made certain aspects less favourable. For example, in the individual phases, students selected certain unit operations because of the opportunity it would give the student to work with friends or similarly tasked peers (strategising to maximise shared conceptual design space). Also, CE participants preferred working with model design solutions, either in the form of published literature (e.g. patents, journal articles) or prior cohort designs - as such designs offered students sources for data/information. In the CE design study, the equivalent to the cost constraint was the page limits. This was reported by Spencer Jennings with respect to the individual word limit and some students who reported that they intended to go over the word limit despite the constraint.

> … I was talking to other people in different groups who were doing distillation column, they submitted their project… Because some of them submitted a day before the submission date and they submitted it like 3800/4000 words. Even though it said 3000, they submitted it with those many words, and they said there was no way for them to get rid of any more words. *- Spencer Jennings*

This suggests that where a constraint is perceived as overly-limiting, this may factor into students' intentional defiance of the design requirements out of concern that further omission would detract from the completeness of the presented solution. Given that the report output *is* the design for CE students such report length constraints have a direct impact on students submitted solutions. A similar sentiment was implied in Goncher's (2012) study given how frequently the budget constraint was defied and superficially approached. In general, the limits to the report length in CE design tended to be considered at the final stages of report writing where students were confronted with the constraint. Goncher explains that:

> Cost was not a salient factor in the early phases of Team 2A's design process in terms of discussion or impact on subsequent design decisions. The design session video data suggests that this team was not conscious of the constraint until they needed to purchase the remaining components not related to the bridge, i.e. turbine, battery, and light bulb. (pp. 87 - 88)

Like DSEP Team 1A, Team 2A did not consider this constraint until later when they are 'faced' with the constraint, when they must report it. Unlike teams 1A and 4A who defied the constraint, Team 2A attempted to abide to the constraint by making changes to their design effectively compromising on quality in their design solution. These compromises relate to many experiences to CE design study participants in relation to the report length constraints, there was an element of compromising elements of the design that is perceived to negatively impact quality but produce a ‘valid’ design output.

> When at the beginning they were like “just fill the brief, it will be a mid-60, if you wanna get into the 80s” - the unachievable marks for me – “you really have to do extra things” and we had done extra things, but we couldn’t fit them in. It’s a 10 page report and your reference list is included in those 10 pages, which you’ve probably heard about already, which was a disaster. And in the interest of concision and filling the brief you’ve got no space to do any… To put in any of the extra work in. I did a full market analysis of all the buyers in [country] and if they had ibuprofen products – I couldn’t talk about that, so it just didn’t make it in. *- Cain Bruce*

> And I read through my report again going “I really haven’t shown the best of what I’ve done.” Because I was trying to get in basics… I think the page limit for phase 2 was harsh. I really do. I think last year, they may be had the same page limit, but they had unlimited appendixes and that made it easier to get across everything that you wanted to get across – even if you can put it in the main body of the report, but five pages for appendixes… And the references included in the page limit is just, just scraps off two pages off your page limit. It should have been 12 pages, but it was really 10 because you had to have all your references. I feel like that encourages people to not reference, and that kind of seems wrong to… Encourages you to not include things because… All we had were two pages of references and had to cut it all back. In phase 1, we were just hacking out references {laughs}. It was mental. *- Ellis Donaldson*

These reflections from Cain Bruce and Ellis Donaldson emphasises the importance of both well thought-out constraints and associated student buy-in. Depending on the constraint type, creativity and demonstration of deep understanding, which are valuable in design contexts, are usually impacted by such constraints. Furthermore, Ellis’s comments demonstrate how such constraints gave rise to practices that were conflicting with the expectations of authentic academic practice, namely employment of extensive literature references. Billy Reynolds mentioned how he had compromised his deeper understanding of a county’s legal system in the phase one report, opting for a necessarily simpler description, similar to Ewan Murray’s account. On the other hand, DSEP Team 1 was able to demonstrate innovative problem solving by making use of a disassembled hand-crank torch to obtain the required components of their design (Goncher, 2012, p. 87). This approach of adapting to constraints was demonstrated in certain groups’ focus on negotiating the report formatting requirements with their supervisors which would possibly allow for more content per page (e.g. changing fonts, margins etc.).

6.5.8 Not Looking Back

One aspect of Goncher's (2012) study of DSEP students was the frequent submissions required from students (almost every week throughout the 8 weeks).

> Focus Group Interview: Kelly: "I like how it was a step-by-step process and something was due each week rather than all at one time because it helped us not fall behind." Eddie: "The whole idea behind it, I think it was better you had steps to complete each time because it made it less stressful. It was more like, 'I have to complete that by tonight' and just do that. As opposed to being like, the entire week, 'I gotta finish this, I gotta finish that'." (p. 70)

Goncher (2012) describes that these assignments were structured "to facilitate students' progression through the design process" (p. 37). As reinforced by Kelly above, these submissions did focus students efforts and result in progress through the design process. On the other hand, these submissions impacted students abilities to revisit design decisions and iterate over their designs.

> Like other teams, i.e. Team 1A and their solar panel choice, Team 4A originally purchased an easily available component found at RadioShack, which after testing they realized it was not the best component for their design. Due to DSEP deadlines and budget constraints, Team 4A found it difficult to go back to earlier phases or reverse design decisions. (p. 137)

The difficulty experienced by Team 4A and difficulty they found to go back to the earlier phases of design, was shared by some participants from student interviewees of the CE Design study.

> "Especially towards the end when you start thinking of things and you're just like "oh God, I never thought about that but I'm just going to have to go with it."" - *Natasha Douglas*

> "That wasn't the case, because I just went with the design that I did instead. Yeah, I dunno, I made assumptions too early on maybe…" - *Will Ross*

> "My separation system is directly after Lauren's, in my group, reactor. She was the one that was having this issue of not finding the kinetics and Peter [Supervisor] suggested to her if it's this particular reactor or this particular catalyst and you can find other things for another catalyst, why don't you just change the catalyst. And her answer to that was"Cain's section is all about catalyst removal". And I was like… "That's true, but you can change it if you want, because I'll probably make my life a lot easier anyway because I'm having my own set of issues." But I think Peter [Supervisor] was a bit hesitant to let that go forward because… I can understand that just from a grading point of view. If we just scrap a whole week of my work. So,

> I can understand that, but I got the sense that if it was in a job, I would absolutely say use the one that you have data on because it will make my life easier as well. It's the catalyst that we are using that's making this difficult. So, the academic constraint has made that not possible, which is a little bit frustrating." *- Cain Bruce*

These CE design students recognised that because of the structure of the phases and time limitations involved in design that it was not possible to review their earlier design decisions in light of new findings, understandings and challenges of design as they progressed. Cain, in reference to individual designs, explicitly mentions the academic constraint of grading and how interdependency of individual designs discounted certain changes. Ultimately, this led to an approach where students had to "make do" with the decisions that had been made, despite being aware of the deficiencies of those earlier decisions and impact that these had on their current design. Interestingly, even though CE design included a reflective review as part of phase three, it was not reported as an important component in their designs. In addition, some students were confused by the idea of design reflection.

These elements of submissions stands somewhat in contrast with both DP1 and DP5 studied by Morgan (2017). The former involved a single final graded submission, however, included a recommended schedule of work as a guide to students. The latter included a "conceptual design" submission approximately mid-way through the design, with the final report and poster submissions staggered around the final two weeks. The CE design study involved three major submissions corresponding to each phase of design, and also involved significantly larger submissions as well. This afforded students significant time to reiterate designs and afforded fluidity in design, at the detriment of the DP5 students, who remained confused and tentative about the design problem and solution until very late into the submission. Goncher (2012) suggests that the while iteration was intended by the DSEP, "due to the demands of the course context, i.e. course planning and deadlines, the structure of the DSEP resulted in a fairly linear process by [sic] students" (p. 135) and highlights the lack of iteration among DSEP Team 4A students in their approach to design.

In the CE design, students found this aspect challenging too, where they became aware of issues in their assumptions related to the initial design decisions which were effectively locked in place. In addition, some students found that they were reluctant to iterate, as, in their eyes, this was effectively making completed work redundant and reversing progress (as mentioned by Cain Bruce). Morgan's (2017) account of DP5 students suggests that this phenomenon was relevant there too, since DP5 was meant to follow on from a design project completed in the year prior. Nevertheless, owing to ambiguity in defining the problem definition, students struggled to progress with later design stages.

In contrast, Morgan's (2017) study of DP1 students appears to suggest that the students were open to iteration - however, there remained concerns around design selection/decisions and much time was spent deliberating whether a given decision was viable and strategising to minimise risk related to implementation of prototypes.

6.5.9 Designing for the Academic Evaluator

Goncher (2012) found that students adapted their submissions related design, such as reports, in order to satisfy the expected preferences of the one evaluating their designs.

> Brett: “Okay so you can do that one. Make sure [to write] the different types of brainstorming. The one method…” Andy: “The trigger method.” Brett: “Yes. Make sure you throw that in there. **She’ll eat that up.**” (p. 104)
>
> Cullen: “Is replenishable not a word?” Brett: “I’m pretty sure it is.” … Cullen: “I’m just going to keep it because I know it’s a word. It’s in the word document. I’m incorporating a bunch of these definitions. **She likes that.**” (pp. 103 - 104)

There was a shared understanding that satisfying the evaluator’s expectations of good design was attributed with more importance than the design process itself. Students’ emphasis of phases of design, in this case the DSEP Team 3A’s views of ‘idea triggering’, was a result of their belief that it was important to the evaluator of design - not because of the value of the design phase and process itself. This suggests that students prioritise the assessor of the design, since the design was necessarily an educational exercise.

In the CE design study, it was found that a prominent function of supervisory meetings was to clarify the brief requirements and draw out the supervisor’s preferences and expectations. This interpretation of the evaluator and their preferences, as a constraint-source and design constraints respectively, was a widely held belief among interview participants of the CE design study.

Students’ appreciation of this contextual factor suggests a deeper understanding of the inherent subjectivity of design requirements and this ultimately framed students’ design decisions. Although it may appear as a supplementary source of constraint, certain accounts of supervision (for example, Frank Hill’s difficulty in obtaining explicit feedback from his supervisor in CE design) suggests that a lack of such a seemingly subjective source of constraint from the evaluator can result in students facing significant difficulty in constraining the inherent open-endedness in design. Ellis Donaldson from the CE design study captured this well in the following excerpt.

> The people who can submit a draft get to know before the submission date what’s good, what’s bad, what their supervisors specifically wants to see… Other people, the supervisors told them specifically “I’m more interested in this, focus on this,” so, how does that lead to a fair mark for people who are getting that vs people were getting absolutely nothing. It’s not fair. - *Ellis Donaldson*

In this excerpt, Ellis Donaldson emphasised the widely held belief that the clarity of evaluator's guiding comments tangibly impacts students' grades by drawing their attention to subjective preferences. Goncher (2012) elsewhere mentioned that as "a basis for decision making, Team 4A often relied on their assumptions of what they thought was valued by the instructor or how they assumed she would approach the evaluation and grading of their design artifacts" (p. 122). As an example, Team 4A used these assumptions of instructor's values to guide their design efforts and "cut corners" in their submissions.

> Channing: "Because I heard they would check for grammar stuff. Like you would lose points for commas out of place." Neal: "On this? I thought I overheard her say she wasn't going to check." Channing: "My friend that took it last semester told me they did check. I don't know if she taught last semester." Neal: "Honestly would she know if it was really…" Cody: "She's obviously not an English major." Neal: "Yeah so. I mean she's got to be like the majority of other engineers out there." (p. 124)

Again, this excerpt directly relates to those found and the CE Design study, where students expressed the importance of obtaining constraints, feedback and requirements from the supervisor in an effort to obtain clarity around evaluation. In addition, certain supervisors in the CE design were viewed as having preferences for specific things that they would like to see in the final designs, such as Cameron Hooper, who owing to his supervisor teaching a class on process control was expected to be concerned about "control over [the] reactor" and that they "have to put a control system in". Personalised preferences and expectations around evaluator's expertise impacted the importance of design aspects and guided students' efforts.

6.6 Summary

This chapter explored the studies of Morgan (2017) and Goncher (2012), applying the same analytic techniques that were used in the study of CE design presented in Chapter 5. The principal codes emerging from both works have been integrated into the analysis of the CE design.

The notable codes emerging from Morgan's (2017) study of DP1 students demonstrate that, given the context of physical students prioritised the functionality in design, engaging in an iterative approach to design through collaborative discussions. There was a strong awareness of the design requirements which informed students practices, with students engaging in actions to clarify ambiguity, through supervisors, around their design solution with respect to those requirements. Students also engaged in process of minimising risks to ensure that their design was viable and informed their design decisions by comparing with previous students' designs and what other groups had done also.

The prominent codes emerging from Morgan's (2017) study of DP5 emphasised the significance of clarity of design requirements, specifically those relating to deliverables of design, and the degree to which competing requirements had significant impact on students design practices. Students also approached design with risk minimisation with respect to their own competencies. The compartmentalisation of their division of labour appeared to add to their inability to define the design problem which they were offering a solution. Supervisory affirmation affected students' abilities to secure their design solutions.

In Goncher's (2012) study of DSEP students several codes emerged as pronounced. Workload; associated grades; and intensity of submissions was reported to impact students' behaviours and priorities. Such perceptions resulted in many students superficially engaging with the design project and trivialising design constraints. Students quickly restricted their design solutions to those that were functional, given the physical nature of their design problem, and possible given their competencies. Students also informed their approaches to design by using information from various contacts who had experience of the design. Furthermore, students' practices were governed by their expectations of what was sought by evaluators of their designs.

Many of these aspects relate to the analyses emerging from CE design, and the next chapter incorporates all these analyses, presenting a cohesive grounded theory.

Chapter 7. Grounded Theory

7.1 Introduction

This chapter outlines the developed Grounded Theory that emerged from iterative analysis of the codes that emerged from Chapter 5 and Chapter 6. The theory is explained by demonstrating how it directly relates to CE design; Morgan's (2017) study of DP1 and DP5; and Goncher's (2012) study of DSEP.

7.2 Comparing and Constraining

The Basic Social Processes (Glaser, 1998) put forward by this study to describe the experience of engineering undergraduate students undertaking design projects are *comparing* and *constraining*. *Comparing* directly relates to students, but *constraining* relates to both how both the environment around design impacts students and how students adopt practices to *constrain* the design environment too. These two processes are closely link and manifested in different ways as students undertake design depending on the context, they find themselves in design.

Comparing captures a significant strategy students employ to make sense of the design problem and solutions. *Comparing* is used as a socio-technical tool that students employed to address open-endedness and complexity in design - thereby *constraining* the associated ambiguity in various design settings. As demonstrated in the previous chapters, students engage in iterative cycles of comparing in order to develop these socio-technical constraints, refining these and informing these in light of emerging details related to design.

7.3 Comparing and Constraining in CE design

A possible understanding of CE design through the lens of comparing and constraining is shown diagrammatically Figure 7.1 and subsequently explained.

In the context of CE design, we find that the process of *comparing* was situated in a wider culture around *sharing* which was informed, in part, with students *being in the same boat* - i.e. their common goals were aligned. Common across both individual and group phases, was the proactive sharing of information between groups. Students "pooled" and "distributed" resources and information to facilitate comparisons and used these comparisons as techniques to constrain their own, and others designs. In general, students appeared to collectivise efforts to constrain their designs.

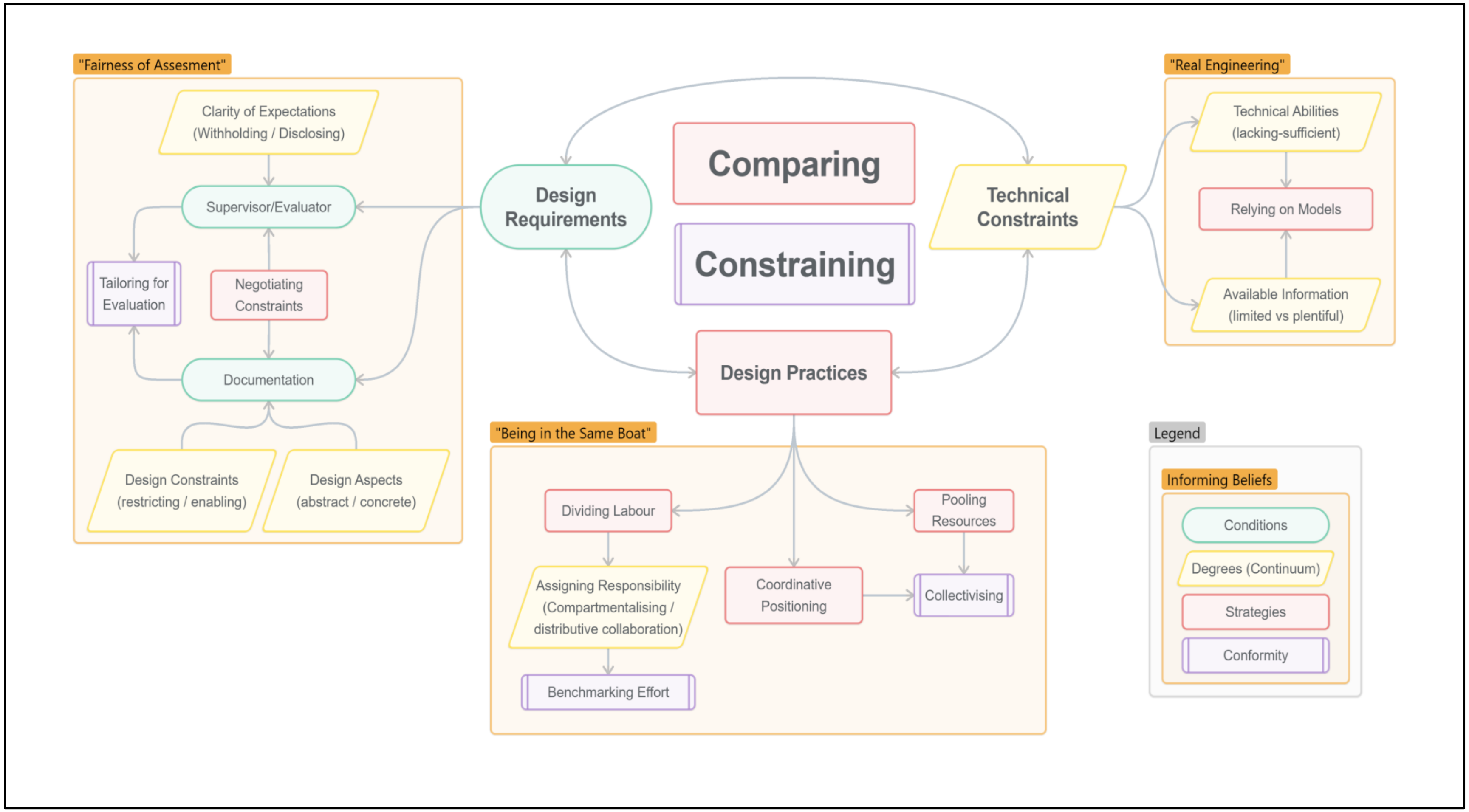

Figure 7.1 Grounded Theory of Comparing and Constraining applied to CE Design

Students, when working in their groups, engaged in iterative approaches to design by *bouncing ideas* off group members, effectively cycling between comparing possible solutions and providing feedback to constrain design solutions. Students in CE design constrained design practices by engaging in a division of labour by adopting either a distributive collaboration or compartmentalisation model. The former involved students sharing responsibility of design tasks with other members (sub-groups) and the latter entailed emphasis of individual responsibility. Students also constrained their design practices, and that of others, by establishing norms around design that would allow for comparing to occur. One significant approach was to work together frequently in physical spaces. By doing so, students were able to benchmark effort - by comparing their own effort with that of their peers they were able to constrain the practices of individual members to align with the wider group, encouraging a collegial environment around design. However, in some instances where students compartmentalised tasks and did not opt to work in physical spaces, students were unable to engage in this self-correcting comparative benchmarking process and the likelihood of free riding increased. Students also emphasised that mere presence promoted better group dynamics.

In individual phases of CE design, students were somewhat 'forced' into compartmentalisation. Almost all students interviewed implied that they joined self-assembled groups of students who shared the same conceptual design space. In some instances, students engaged in coordinative positioning - that involved strategically opting for designs that would ensure there was conceptual overlap with peers in other groups to ensure that these self-assembled groups could form.

Such aspects of CE design demonstrate the strong understanding students have of the educational context of their design projects. These self-assembled groups formed to facilitate the same processes of *comparing* and *constraining* that were possible in students' original groups and were largely cohesive to the extent that their conceptual goals aligned.

Students' perception of their own technical abilities and the available information for subsequent detailed design tasks, resulted in a tendency to take an approach which involved basing their design on existing models. Such models ranged from patents to prior cohort's designs. The design requirements impacted the technical context of design as the design problem as set out in the brief was found to restrict the design space which in turn impacted the possibility of demonstrating originality in design. Students' proclivity for relying on models was a practice they adopted to constrain the technical ambiguity in their designs.

Students in CE design also used the process of comparing and their belief of *fairness of assessment* to constrain possible design ambiguity. In CE design, it was found that many students constrained their designs by relying on the requirements as set out in the brief by *"playing by the book"*. Students in CE design were cognisant of the assessment, and so aligned themselves very closely to the way in which evaluation would be completed. However, such design requirements could include overly restrictive design constraints which students, in general, responded to by superficially conforming their designs to - ultimately, compromising on quality. Students did attempt to overcome restrictive constraints, by engaging in cycles of interactions with supervisors to negotiate these.

Supervisory comments were, then, also used by students to constrain their design practices. Supervisors were understood to be the customer of design, a belief which is grounded in the role CE design supervisors have as evaluators of design. However, supervisory clarity around their expectations were deemed (and observed to be) variable, with some supervisors withholding and others disclosing expectations.

Specifically, this focused on conflicting constraints that emerged from expectations set by supervisors of design. Students used supervisory comments, feedback and expectations in order to constrain their own designs and also negotiate these by employing comparisons. However, students also used comparisons of different supervisors' comments to further constrain the design requirements - which they generally felt should be consistent. When students compared supervisors' comments and identified differences, students engaged in negotiations with their supervisor to address the differences.

7.4 Comparing and Constraining in DP1 (Morgan, 2017)

In the context of DP1, the students engaged in *comparing* as a socio-technical tool within their group interactions to manage their perceptions of, and practices in, the design task.

This was evident in how they frequently shared their evolving designs and solutions during the weekly sessions, promoting collective decision-making. The act of *comparing* their ideas against each other's work helped the students to identify feasible approaches and constrain ambiguity by adopting the best ideas within their group. The frequency with which they engaged in these iterative feedback loops, allowed them to *constrain* their design options to more viable and achievable solutions. Facilitating these interactions was a shared physical space where students engaged in the design activity regularly. The students also engaged in a distributive collaboration model around their division of labour.

The students faced limited technical constraints tied to their own skills, with an understanding that they would be supported in technical development through support that was available to them. Students compared their solutions against pre-existing models, or models of others, to inform their development and design decisions. However, their willingness to conform to these models varied; some students demonstrated a preference for innovating beyond the constraints of available models, while others strictly adhered to "proven methods" to minimise risks to ensure that their design is functional, informing this were the design requirements as set out in the brief and negotiated with supervisors.

The design requirements were explicitly and concretely outlined through documentation provided at the project's inception and continuously refined through direct communication with design supervisors. Students engaged in regularly *comparing* their work against these requirements, demonstrating an alignment to these goals.

This process of comparison was heavily influenced by the documentation and feedback provided by the supervisors, who acted as the primary gatekeepers for what constituted an acceptable design approach. The supervisors' input effectively helped students to *constrain* their creative explorations, ensuring that while innovation was encouraged, it remained within the boundaries of what was feasibility.

7.5 Comparing and Constraining in DP5 (Morgan, 2017)

In DP5, the students struggled to effectively leverage *comparing* and *constraining* as a tools to make sense of their open-ended design problem. The primary issues faced by the students were that of competing and conflicting requirements emerging from two different sources (educational supervisors and commercial sponsor) and the inability for students to concretely constrain these, despite attempts to do so.

The educational design requirements for DP5 were articulated through documentation and guidance from academic supervisors. However, the students' approach to *comparing* their designs against these requirements were lacking; aligning themselves to the requirements set by the sponsor - whom the students had limited interactions with. There was a tendency to overlook critical feedback from supervisors or to misinterpret requirements. This lack of proper comparison and alignment with the project's core requirements meant that the students' design practices were largely *unconstrained*.

Supervisors provided limited input that could have been used as a key source through which students could constrain their design options more effectively, with the educational supervisor withholding feedback in general. At the onset of the DP5, it was clear that there were tensions between the requirements of the project sponsor and those of the academic supervisors, which significantly impacted students' ability to interpret requirements. DP5 students struggled to integrate and compare their designs to the academic requirements which meant that their work remained perpetually tentative with students demonstrating significant uncertainty around their design, even late into their project. As a result, the *constraining* process was not guided by a strategic alignment to the educational requirements of design to inform their key decisions, but rather involved instances of superficially conforming to these aspects.

Their group interactions showed a lack of effective comparison of possible design ideas and solutions, with most of the students' interactions spent focusing on resolving the ambiguity in the requirements. Instead of using comparisons to refine and converge on an understanding, the students tended to agree superficially, which impacted their ability to explore alternative solutions. Contributing to this may have been the group dynamic, which fostered a false sense of consensus, owing to the students' approach of compartmentalisation of their design tasks. Without enabling opportunities for debate and critique, the process of *comparing* fell short of its potential to constrain design choices meaningfully. This lack of critical comparison led to a fragmented approach to their design, where shared understanding of the holistic design was limited.

The students faced several technical constraints related to their own abilities. The context of their design was largely abstract, related to systems, which the students struggled to compare effectively with previous work, or that of others. As such there were limited instances where students used *comparing* to benchmark their design, which may have aided them in constraining their conceptions of the design. The students' constrained their designs based on their technical abilities, opting to avoid aspects that were deemed too difficult for them to achieve, but to constrain their design to the educational requirements, introduced technical components.

7.6 Comparing and Constraining in DSEP (Goncher, 2012)

Within the DSEP project, *comparing* played a crucial role in shaping how students engaged in their design. Informing the students approaches was the wider institutional constraints related to balancing other classes and the limited grade impact associated with the project. DSEP students constrained their design practices considering these factors.

Groups often engaged in comparative discussions to evaluate their design ideas against those of their peers. This process allowed them to collectively navigate the open-endedness of the design problem, narrowing down potential solutions through the act of *constraining* choices. Such comparisons were not merely technical but also social, as students relied on dialogue and negotiation to reach consensus. By comparing their ideas, students effectively constrained ambiguity, ensuring that the chosen designs were feasible and aligned with group expectations and skills. Furthermore, comparing also led to many of the design teams under investigation dealing with design requirements superficially. These comparisons, with others who had experienced DSEP before and those currently undertaking it, along with significant restrictions in constraints (i.e. cost), even resulted in fraudulent reporting within design.

Students faced several technical constraints related to their skill levels and available information, which impacted their ability to explore more innovative solutions. In these scenarios, *comparing* their work with existing design models or the outcomes of peers provided a reference point, helping them stay within their technical limits. This approach of benchmarking against known models helped in *constraining* choices to what was practically achievable, minimising risk. However, this reliance on comparisons could sometimes limit creativity, as students might prefer safer, more familiar designs over more novel approaches.

Hence, while comparing models was useful for learning and feasibility, it could also unintentionally discourage exploration of more innovative paths.

Design requirements in the DSEP were clearly defined through documentation provided at the outset and were reinforced by supervisors throughout the project. These documents acted as a foundational reference for *comparing* students' ongoing work against the stated objectives and constraints. Supervisors played an integral role in guiding students to align their designs with these requirements, offering feedback that frequently prompted students to re-evaluate and adjust their designs. This iterative process of feedback and adjustment illustrates how *comparing* was employed to align design efforts with established criteria, thereby constraining the development process within the framework set by the project's documentation.

7.7 Relationship to Other Work

The Grounded Theory constructs of Comparing and Constraining can be compared to other literature in the substantive area and fits.

Hart & Polk (2017) collected survey responses on two occasions from engineering cohorts made up of mechanical, biomedical and electrical engineering students to assess which factors influenced students selection of capstone design projects. They found that among the most important factors for students were that projects "had well-defined requirements and goals" and "quality of information before selection" (p.1423).

More recently, Stresau and Steiner (2020) used a mixed methods approach case study to investigate the factors which impacted student success on capstone engineering design projects. Among their findings they note "that teams with a clear and early understanding of project requirements were more satisfied and engaged. Conversely, students on projects with unclear definition were less satisfied" (p. 15).

Both these findings triangulate well with the presented work, where among students' salient concerns involved obtaining clearly defined project requirements so that they were able to constrain their designs to meet those requirements. Students align their practice to requirements approach in design and so, the importance of well-defined, or clarifiable, project requirements cannot be understated.

Lawanto (2010) investigated the changes in metacognitive activities of engineering students engaged in design projects and found that certain external aspects of design impacted these. Complexity of problems, time constraints, lack of resources, and external help or suggestions were found to impact metacognitive changes of engineering students.

These findings align with the grounded theory presented. Students attempted to resolve the complexity of the problem by comparing with peers to engage in iterative feedback loops. Students align themselves to design constraints such as time and adapt their design practices to comply with such constraints, usually by compromising on quality of their solutions. The grounded theory also demonstrates how students made use of the context of design, and their understanding of the culture to connect to peers to “pool resources”. Finally, students proactively engage in iterative feedback loops with peers to obtain help and feedback; but also use wider information from previous cohorts too. Students, when forced to compartmentalise, also managed their design practices to facilitate comparisons in self-assembled groups.

Paretti (2008) explored communication practices in a case study of capstone engineering design projects and followed two student groups. The first is described as having “argued openly that certain requirements (e.g., mass and energy balances for their system, a process flow diagram) not only did not make sense, but were meaningless with respect to the scope of their project” (pp. 498 – 499). The other group, “in contrast, adopted a very positive attitude toward the course and the [course co-ordinator], and clearly wanted to fulfill requirements and provide necessary information” (p. 499).

The above excerpts highlight how within the same institutional context students design practices can vary significantly. The first group demonstrates an attempt to negotiate the design requirements on account of relevance for their project, whereas the other group demonstrate constraining their design around the design requirements, as they found the relevance in these to their design practices.

Altman and colleagues’ work (Atman et al., 1999, 2005, 2007, 2008; Atman & Turns, 2001) on verbal protocol analysis of freshman and senior students and professional engineers design processes found that student engineers tended to fixate on modelling (detailing how to build solutions) very early on in short-term individual design tasks when compared to professional experts. In addition, professional engineers also tended to spend more time defining the problem, gathering information and evaluating feasibility and frequently iterated between these stages during the design process. Although, these were short-design experiences in the range of several hours, the findings here align with the theory presented, especially in terms of student processes. The early fixation on a given design, or model, tended to be associated with students attempting to address the open-endedness in design by adopting models and fixating on the particularities of a single solution.

While, the theory does not capture the specific practices of professionals, the theory can accommodate expert engineering designers’ practice of spending more time defining the problem, gathering information, generating ideas and, ultimately, delaying model building. A perspective from the process of annealing metals may be a helpful metaphor to describe this (Gale & Totemeier, 2004). This suggests that at the early stages of design work it is critical for students to be more tolerant of ambiguity and defer processes constraining early on, with more focus on technical comparisons. This would be akin to a “high temperature” when annealing which allows for greater acceptance of variability in possible solutions. As the design progresses, designs should be constrained slowly, ensuring that the design is sufficiently constrained by the end of the design process. The annealing analogy holds here too, where the temperature is cooled at a controlled rate to impact the material properties of the metal.

Linked to the these ideas around fixation, is the work of Toh and Miller (2015, 2016) who have investigated the creativity of students at various stages of a short-duration design activity. Among their findings were individuals' tolerance for ambiguity was related to greater novelty in idea generation; individual risk aversion was linked to favourability of quality over creativity in design concept selection; and creativity in individuals' idea generation was not related to creativity in concept selection (Toh & Miller, 2016). Their work on teams creativity (Toh & Miller, 2015), however, uncovered that concept selection was largely accompanied most frequently with discussions around the technical feasibility of ideas, followed by comparisons with other ideas and comparisons to existing products. There is clear alignment with the presented grounded theory, while more encompassing than the specifics of the design activity, and the emphasis of *comparing* design concepts to other generated ideas and existing products in order to select or *constrain* the design that is carried forward. These investigations are focused on shorter design sessions, however, and the presented grounded theory demonstrates how comparing and constraining processes manifest in much more encompassing and situative ways in sustained design activities.

Considering wider perspectives on design, Bucciarelli (1988) in his seminal work, "An ethnographic perspective on engineering design", introduces one of the first examples of in-depth qualitative inquiry using participant-observation methods in engineering design projects to explore design, albeit in a professional setting. In this work, the paradigm of design as a *social process* is adopted and the view that physical representations of design are simply artefacts of a more enduring process that outlasts such productions. Interestingly, Bucciarelli suggests that these artefacts, be it a prototype or specifications or reports, do not necessarily reveal much about the process that brought these about. Anecdotally, design educators may be all too familiar with the incongruity of the design *as the process of interactions* and how this can differ substantially from design *as the final product*. In the context of the grounded theory developed, there was demonstration of how the requirements were at times superficially considered and in the case of some of the DSEP students they adhered to design requirements through the false presentation of processes. Here the production involved intentional misrepresentation of the process.

The theory also integrates with the perspective of other design researchers such as Bogford-Parnell et al. (2013) who state that regardless if "…the team design process is described as a series of negotiations, a cycle of figural and conceptual reasoning, or a reflective conversation; it is well-accepted that the individual members of a design team interact with and influence each other's thinking" (p. 81). These not necessarily be, at least for students, those on the same design team, as per the definitions set out by the authors. Students observe members of design behind the formal team, emerging from the context. These have included senior, experienced peers; supervisors, their own and others; and peers who were not formally part of students' design groups. All these members are possible designers from a social perspective, in as much as they can influence students' design practices.

In their grounded theory analysis of semi-structured interviews with product engineers about engineering problem solving, Itabashi-Campbell and Gluesing (2013) determined characteristics of successful and unsuccessful problem solving:

> Successful problem-solving efforts, at least in our sample, received clear leadership guidance, were unconstrained, were associated with controlled urgency, had adequate resources, and utilised an available framework for sharing. They moved with a clear cadence, leveraging stakeholders' knowledge and skill sets and ultimately unifying everybody's point of view. They culminated in positive system changes and conclusions that "made sense''. Unsuccessful problem-solving efforts, on the other hand, had limited leadership guidance, were more constrained, were more chaotic or inertial, had inadequate resources, and showed limited sharing. They were less systematic and were not sufficiently able to unify stakeholders' cognitive perspectives. They did not effect positive system changes or deliver closures satisfactory to the product engineers" (pp. 130 – 131)

There are several aspects which connect well to the grounded theory presented in this thesis. The authors assume *clarity of external leadership vision*, where the designers were supported, often directly, in the problem-solving endeavour. Such affordance of leadership in academic design projects was not always possible, especially where the academic adviser held an evaluative role in design projects. Unlike the students considered in this thesis, the design engineers valued *autonomy* as a favourable condition for problem solving. Both engineers described here and the students undertaking design projects required appropriate *resources*, specifically appropriate people, to tackle the design problem. Students, where they found such resourcing lacking, for example in the CE design study, ensured access to the right people through their understanding of, and interaction with, the social environment. Finally, *frameworks for sharing* involved being able to communicate effectively and share knowledge and information. Students proactively shared resources in order to tackle the design problem and demonstrated that these frameworks for sharing were built on pre-design experiences.

Itabashi-Campbell and Gluesing (2013) also described *cognitive convergence* as a process-view for successful problem solving, with the participants emphasising quick orientation to problems and involving the correct individuals as features of such convergence. This goal may or may not be achieved in the context of educational design projects. There are clear parallels to students' constraining practices to develop a collective understanding of design and the notion of *cognitive convergence* described here. Critically, students tend to employ a situation-specific approach to achieving convergence by adopting collectivised practices.

With respect to design theory, the action-interaction involved in comparing is a socially-driven process that aids students in framing design (Dorst, 2011; Schön, 1992). Adams et al. (2018) describe "[p]roblem framing [as] the process of formulating a problematic situation – organizing and clarifying both the ends to be achieved and the means of achieving them" (p. 38). Students, like other designers, will utilise their prior experience and interactions to construct frames which relate working principles of design with value generated. Dorst (2011) suggests that designers work back from the aspired value that the design is meant to generate to simultaneously develop the design solution and working principles, however, as evidenced in CE design and Morgan's (2017) DP5, a significant challenge for students in increasingly abstracted and larger-scale design is concretising the value to be generated itself.

It can be argued that students lack sufficient experience of design, with a limited repertoire of frames and, where possible, comparing with others is a situated approach for students to generate and develop frames in a socially-driven manner. In CE design, it was found that students utilised existing models of design, which can be interpreted as "off-the-shelf" frames, however these frames where adopted were relatively quickly incorporated into design and students tended to maintain such frames despite experiencing significant design challenges or even upon realisation of deficiencies in emergent solutions. Comparing, then, acts as a process through which design frames are not only developed but also maintained, ultimately constraining the perspectives with which the designs are interpreted. This is where students actively avoid competing frames which may result in significant redesign.

Furthermore, students framing of design problems are very much situated in the educational context, and hence students carry the learned frames of working principles and values gathered from the entire university experience preceding design work (Dannels, 2000, 2003; Goncher & Johri, 2015; Paretti, 2008). Such values can relate to how typically solutions outside of design are deemed either 'correct' or 'incorrect', which is a belief that permeates into design; or whether a solution is similar to peers' solutions; or whether a solution addresses the expectations or preferences of the evaluator. The associated working principles of resourcing and comparing practice, information and solutions, relate to the "how" of design which students have employed and learned previously in their studies to aid in achieving those aspired values. Comparing and constraining, can be thought of as, approaches to framing design problems.

7.8 Summary

This chapter presents the grounded theory relating to experiences of engineering undergraduate students undertaking design projects and introduces the salient social processes of *comparing* and *constraining*. *Comparing* involves evaluating various design ideas and solutions to make sense of open-ended problems; while *constraining* refers to the methods used to limit the design space and reduce ambiguity. These processes relate to social dynamics (such as collaborative efforts and information sharing) and technical factors (like minimising risks and relying on models). Students use such strategies to refine their designs iteratively, aligning with project requirements, managing complexity, and ensuring feasibility. Supervisory feedback also plays a crucial role in guiding these processes, with effective feedback helping to constrain creative exploration within feasible boundaries.

The application of *comparing* and *constraining* varies across different design project contexts (e.g., CE Design, DP1, DP5, DSEP). For instance, in some projects, students effectively utilised comparisons to align designs with shared goals and technical constraints, while in others, conflicting requirements and limited supervisory input led to fragmented and uncertain design approaches. Challenges often arise in balancing innovation and constraints, as adhering too strictly to existing models can limit creativity, whereas unclear constraints can result in superficial alignment and compromised design quality. Overall, these processes are crucial for navigating design complexities and aligning educational objectives with practical outcomes in engineering education.

Chapter 8. Conclusions

8.1 Introduction

This chapter begins with a review of the study and main findings. Implications for practitioners of engineering are then discussed as these relate to educators and students undertaking engineering design projects. The chapter concludes with limitations and future work.

8.2 Review of the Study and Findings

Despite an initial interest in competency development, the study described in this thesis evolved and aimed to develop a rich, qualitative insight into the salient concerns of students undertaking engineering design projects. These design projects were understood to be themselves important experiences for engineering students and offer students opportunities to develop complex engineering competencies that are difficult to teach (Dym et al., 2005). Furthermore, these design projects are highly situational, where nuances in the environment of design can significantly impact students design practices (Goncher and Johri, 2015). The research questions that this work aimed to address was

> **RQ1:** What are undergraduate students salient concerns related to engineering design projects?
>
> **RQ2:** How do undergraduate students manage their concerns related to engineering design projects?

In order answer these questions a Grounded Theory approach was taken to explore the design project delivered to undergraduate students studying chemical engineering at the University of Strathclyde. Chemical engineering design (CE design) focuses on the design of design processes and unit operations, a relatively abstract form of design compared to other engineering disciplines which may involve design of functional products or prototypes.

The grounded theory approach involved an in-depth study of the context and incorporated various data collection strategies, including observations of design supervisory meetings and documentary analysis. The main data collection strategy which informed the coding process was student interviews. It was felt that this approach was the most reliable way to understand students design practices - by giving their voices and meanings a central position in the research (Charmaz, 2014).

The coding process revealed that the CE design was highly complex and depended and was highly dependent on the setting. Through the coding process it was clear that students' significant concerns were situated in the specific context of design. Coding revealed that students' practices were not simply affected by the context, but also attempted to shape the context by engaging in practices such as negotiating constraints and adapting their behaviours in light of design constraints.

The students in CE demonstrated how perceived deficiencies in support were overcome by students by adopting practices enabled by the norms of sharing which manifested in multiple ways. Students engaged in pooling information; sharing supervisory comments; sharing obtained design reports; and self-assembled into groups of similarly tasked peers when undertaking otherwise individual design. Students also engaged in overcoming technical difficulties by relying on models of design to support their design decisions. Other beliefs around "real engineering" and the dichotomy between the educational context and the notions students had of professional practice were also aspects mentioned by participants. Students also arranged their working practices to facilitate communication and feedback from group members by working in proximity with one another. These also facilitated in students being able to self-correct individual members behaviours around presence, effort and contributions.

Such practices may be unique to the context but offer an insight into the complex social dynamics involved in engineering design projects. To further support claims made by this theory, two studies (Goncher, 2012; Morgan 2017) which included rich narrative accounts and excerpts were analysed and introduced into further analysis, connecting to the developing theory, as recommended by proponents of grounded theory (Glaser, 1998). These studies offered further insight into the various conditions that impacted students' practices.

Morgan's (2017) DP1 study participants' practices centred around iterative-peer feedback loops to constrain their design solutions, facilitated by a structured and clear source of design requirements, and regular physical interactions. Students centred their design around functionality, but nevertheless compared their work to other models of success to provide verification of their decisions. Morgan's (2017) DP5 study participants, however, struggled with an open-ended design problem, with competing stakeholder requirements. Their focus was on attempting to define their problem, and did not align their practices to the educational requirements of design. The students constrained their designs based on their technical skills but struggled to constrain their practice in light of the limited supervisory feedback they received.

The grounded theory presented integrates the findings from these studies finds that *comparing* and *constraining* were the main ways in which students overcame their salient concerns around the open-endedness and ambiguity of design. *Comparing* directly related exclusively to students using comparisons as a sense-making tool but *constraining* reciprocal process of students constraining their design practices in light of the design situation and how they also engage in practices to constrain the environment too. These constructs demonstrate how students interpret their design environment (RQ1) and how they engage in adapting practices and shaping their design environment (RQ2)

8.3 Recommendations for Practice

It is clear that the conditions of design have significant impact on students' design practices and course coordinators and involved instructors must think carefully how they plan engineering design projects. Requirements of the design and technical aspects will constrain students design practices and students may respond in turn through processes of comparing and constraining. While requirements can be ambiguous, owing to the nature of a given design project, these should be consistent with the desired outcomes and not meaninglessly constrain students design practices.

Both educators and students involved in engineering design projects are constrained to the academic context. Since grading is a component of education, evaluation will always involve some form of grading. This is a significant challenge and indeed was recognised as an aspect that can be problematic for students to resolve where differences in experiences emerge in the same cohort. One solution would be to increase the transparency of grading and develop evaluation criteria with clear definitions that is disseminated to students to make the educational expectations of design as clear as possible. These should be well thought out and must integrate well into the learning objectives for the specific design project. Further, the process for evaluation should be made explicitly clear to students to build trust in the evaluation process.

Evaluation should also place emphasis on students' skills and performance, and not only on finalised design outputs. Reflective logs can be powerful tools for encouraging students to reflect on the challenges they face, how the plan to overcome these and strategies they have employed.

Another consideration educators should make is in relation to project supervision. Supervisors have a significant impact on students' design formulation. While supervisors should offer a consistent level of support to students, this is difficult to achieve in practice, especially when multiple distinct supervisors are involved. Training may help but supervisors, just like students, come to design with their own preferences and approaches. Differences in supervisory styles should be celebrated and, perhaps, complemented by assigning multiple supervisors to groups which will give exposure to staff to other supervisory styles. This, of course, is limited by ever dwindling resources. The role of design coordinators is important in this case to facilitate discussions across supervisors by arranging meetings to share best practice.

Reassessing the roles of supervisors and their involvement in evaluation may also assist in abating confusion around acceptable interactions and involvement in design. Supervisors could evaluate professional competencies and evaluation of the final design outputs could be the subject of a team of assessors. Role-playing may also prove to be an effective strategy to encourage staff to approach their involvement in design as an intelligent customer, who can offer insights into the design process but also provide constraints. The role of the supervisor on design projects should be to guide students through design by offering generalised strategies to overcome common issues around limitations in data and dealing with complexity through simplifications and revisions.

Another approach to encourage creativity could be the incorporation of more variation in design problems, by allowing students to be involved in conceptual design projects where they are not obliged to demonstrate practical or finalised design solutions.

Students on design projects should be encouraged to work frequently with one another as part of their projects. Encouraging students to do so allows for a more holistic understanding of design and enables students to engage in peer-feedback loops more regularly in an informal manner. This would discourage students approaching design in a compartmentalised approach. Where such practices are not possible, peer-review could be used to facilitate students' abilities to provide feedback directly to peers. For example, requiring students to submit draft work as formal submissions and assigning other group members as reviewers ensures students can retain connection to other parts of design.

With respect to competency development, it is clear to see that the perspective of design as primarily a social process demonstrates, and this thesis presents, the complexity of lived experience when considered in context. In design, interpersonal skills are necessary to navigate the myriad of social interactions faced by students: from negotiating with supervisors, to engaging with peers and utilisation of community networks. Effective collaboration in teams may vary, but there appears to be significant benefits of physical co-location for design work as a self-correcting mechanism for students' cooperation. The functions and rationale behind the utility of various design 'reports' and associated expectations is also important for student engineers to appreciate. One aspect of competence rarely addressed in detail in the competency literature is the *situative-competency* demonstrated by the various design studies presented in this thesis. Situative-competence captures the depth of understanding about the setting where design takes place, the actors involved, and the associated rules. From this perspective, activity theory (Engeström, 1987), as a meta-cognitive model for situative-competence, is a useful framework that instructors of design should consider teaching to students in order for them to reflect on their design practice.

8.4 Limitations and Reflexivity

The work is limited by the nature of qualitative inquiry and so does not propose that the findings here are generalisable to all engineering undergraduate design projects. The presented results, from its namesake, was grounded on the data that I had collected and ultimately, my selection of data was what I had deemed to be important based on my understanding of the participants comments. It is entirely plausible for others to have approached this study in a similar approach and reached different interpretations. Grounded Theory, as I understand it, requires that a theory presented is modifiable in light of new insights, so I do not claim that the research is conclusive in any sense. It is also likely and expected that the theory may change in light of further study beyond the thesis.

I also limited myself to transcripts of interviews as the main data collection process, although many recordings of supervisory meetings were made. I attempted to capture the main processes in my field notes, but of course may have gravitated towards those aspects which may have appeared important at the time. For earlier observations, this was certainly the case when, with my limited experience where I focussed on minute details which, upon review, were not significant.

Although Goncher's (2012) study took place in the US, the research nevertheless only considered experiences of students in a western university higher education context. This means that there is a lack of consideration of cultural differences that may also impact design practices. This is a significant limitation of the work and as a result these findings will be limited in scope and cannot be professed to capture regional nuances.

The lived experience of research will always be difficult to fully reproduce in research. Researchers may have a much richer and nuanced understanding of context, conditions and culture of their research setting. Subjective interpretations can offer beneficial insights for readers - such as Morgan (2017) who added plentiful contextual comments about the atmosphere in the interaction between members to convey the *feeling* of the interactions, which can become lost in verbatim transcripts. I have tried to follow this too in my analysis of students' practices, by offering insights into context that may clarify what I felt to be missing from transcripts. These are subjective affordances made in the hope of providing clarity for the reader but are, again, interpretations and so cannot be conclusive statements of fact.

8.5 Future Work

Although the relevance of this work to the existing literature has been demonstrated, further integration into the literature would prove fruitful.

Future work should explore possible applications of these concepts of comparing and constraining in other fields of studies. The study demonstrates that comparing is among the main social processes involved in engineering but may also have relevance to non-engineering fields too.

The research could also expand to capture diversity of cultural setting. By exploring non-English speaking countries more nuanced understandings of students' design practices may emerge that yield further analytical insight into the core processes around design.

The work, like those of Goncher (2012) and Morgan (2017) was for this study, should be incorporated into other researchers' analyses for their own studies in adjacent fields and incorporated into different interpretive approaches. For example, the research could be reinterpreted using Genre Theory or Activity Theory to develop further insights (Paretti, 2008).

8.6 Summary

This chapter concludes the thesis with a review of the study and associated findings; implication for students and educators involved in undergraduate engineering design projects; limitations of the study and suggestions for future work.

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Appendices

A1. 2017 CP407 Design Project Brief

UNIVERSITY OF STRATHCLYDE
Department of Chemical & Process Engineering
Chemical Engineering Design Project (CP407)
Academic Year (2016-2017)
Production of Ibuprofen

The Aim of the Design Project

Chemical Process Design is a core module for IChemE's basis for accreditation and CEng award. Through this, IChemE wishes to prepare students for a taste of chemical engineering design project as would be practiced in industry. Although this is a much simpler and less specialized process compared to the "real thing", there are some mandatory items –

- Addressing an open-ended task (skills and creativity)
- Working in a team (skill)
- Ability to organize a group to deliver outputs (skills)
- Ability to produce a group report and present to a high standard (skill)
- Manage tasks, deadlines and deliverables of a task (skills)

And synthesize all the chemical engineering that you have learnt until now:

- Material and Energy Balances (Process analysis)
- Carry out research on regulations, environmental needs (Environmental Assessment and Technology)
- Ability to respond to technical task and calculations required by an engineer
- Process Flow and Instrumentation – systems and their diagrammatic representation
- Address sustainability issues of a process (Sustainability and Ethics)
- Determine the safety of a process and address issues arising from safety considerations (Safety and HAZOP)
- Determine economics of a process (Process Economics)

Therefore, the Design project aims to mimic these requirements by challenging students to carry out technical calculations for design and also determine the economic, sustainability and environmental impact of a process.

Minimum requirements are set by IChemE (and this is pretty rigid) – this dictates learning outcomes and content of the project, and form an essential item for becoming Chartered engineer, and perform as a "professional". This Design Brief is provided to the students to address these aspects. Therefore you have to perform the tasks which are required, which are:

1. Work independently as a group and as an individual on different parts of the project (as required)

2. Show that you can attain the skills level expected

3. Demonstrate that the level of technical knowledge that you have is commensurate with IChemE's expectations

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Introduction

Ibuprofen (2-(4-isobutylphenyl) propanoic acid) is a well known non-steroidal antiinflammatory drug, widely used as a common painkiller. The drug was developed and patented just over 50 years ago in the UK by the Boots Group. Under the patent protection Boots had an exclusive right to make and sell the drug. The patent system protects the interests of companies that develop drugs, so that they can sell patented drugs exclusively, normally for 20 years from the patent award. This allows them to recoup the money spent on a drug's development and also make a profit, some of which will go to investments in new drugs. The original ibuprofen patent ran out in the 1980s, and after then any company could make and sell the drug. Ibuprofen became available on prescription in the UK in 1969 and without prescription in 1983. The current UK market for all approved over-the-counter pain-killers, including ibuprofen, is worth several hundreds of millions pounds per year.

Medicines often have more than one name: a generic name, which is the active ingredient of the medicine, or a brand name, which is the trade name the manufacturer gives to the medicine. The generic name is the official medical name for the active ingredient of the medicine (such as ibuprofen). The brand name is chosen by the manufacturer, usually on the marketing basis. There are many brand names used for ibuprofen containing medicines, e.g., Advil, Brufen, Motrin or Nurofen. Many developing countries are slowly taking the view that they could produce ibuprofen (under license) as a generic drug within their own country, which would be less expensive to their populations.

The Task

There has been considerable interest from overseas companies to produce ibuprofen locally. Your class has been identified to help the licensor to determine whether it is worth allowing overseas licensees to produce this drug locally. There are many countries, both in the EU, Asia and Africa where this drug could be manufactured. The list of countries and the volume of production which the licensees wish to produce are shown below.

In this regard, your group has the task of producing a preliminary design of a process to manufacture **ibuprofen starting from isobutylbenzene.** The product must have purity of at least 99% by weight. The volume of production and location is shown in the following table. Before you commence the technical design you are required to review the economic, environmental and regulatory framework at these locations. In addition, you may wish to examine the laws governing drug manufacturing and price controls (if available) for the particular locations. Your design must conform to the latest environmental standards and must aim to **minimise waste and any effluents** to the environment and **maximise the utilisation of inputs**. Your design must aim to match the energy consumption of the most efficient plants already in operation.

Group	Volume of production (tonne)	Country
1	2000	UK
2	2000	India
3	2000	Iceland
4	2000	Romania
5	2000	Bulgaria
6	2000	Argentina
7	2000	Brazil
8	5000	Germany
9	5000	Sweden
10	5000	India
11	5000	Romania
12	5000	Bulgaria
13	5000	Argentina
14	5000	Brazil
15	10,000	India
16	10,000	Brazil
17	10,000	China
18	10,000	Japan
19	10,000	USA

You can assume there are no restrictions on the space available. You need to ensure that there is ready transport access and if needed, sufficient electrical generating capacity exists within the area. The main material inputs will be delivered to site via road. The economics must be based on the tax regimes existing within the country (if available). In the absence of such data, you may assume UK tax basis, but need to caution the reader to this assumption.

In essence, through the scoping phase you may need to think of the following issues:

1. Is there a method of energy optimization
2. If there were methods for using waste heat, what could be done
3. What sort of reactor would you choose and why
4. What are the hazards and risks that the plant poses during operations?
5. Is the regulatory regime hostile/encouraging for overseas investment?
6. What are the transportation costs to the site?

Some of these questions need to be addressed as a group, whilst others you will need to address as an individual.

***For example**, regarding the Location …*

The answers to many of these questions will depend on the regulations of the country and perhaps the region. You may assume that that the site is level and there are no restrictions on the space available, but you may need to pay higher rent or acquire the land – and that land purchase may have associated restriction. You will need to check that there is ready transport access and if needed, and that sufficient electrical generating capacity exists within the area if you are considering high volume production. You will also need to think about the volume of production – if there is a market for it. Based on that you may need to make an adjustment to the volume of production.

***For example**, regarding choice of Chemical Routes and Material and Energy Balances…*

One of the outputs of this part of Process Design is to choose the process chemistry (or route) for production. This will dictate your needs for materials and energy. Whilst some routes may look easier and provide better yields, they may become operationally expensive due to the continual need to purchase expensive catalysts. You need to determine the material and energy balances for the process and also is these are in supply at your location in adequate quantities. You need to make a preliminary check if there are suppliers for your needs, and how you will access them.

Therefore, as a group you need to make choices and express clearly why these choices have been made. All rationale for your approaches must be stated clearly in the reports/presentations which will be used for assessment.
The following section provides some guidance of what you can expect during this class, and you must prepare to work individually and in groups to get a good mark. Some of these aspects are discussed in operational matters.

Operational Matters

It is important to realise that there is too much work in the Design Project for one or two persons to ***complete individually***. Therefore the project should be broken down into tasks. The student(s) allocated a task is responsible for reporting to the group regarding that ***task in good time so that the group can proceed with their work***. The group should aim to meet ***at least twice each week*** to share information, record minutes of this information and check if progress against main objectives were being made. This record should be available at the supervisory meetings, if necessary.

The group will be allocated a supervisor. The supervisor is an advisor (and not a tutor). For example, the supervisor can advise you on how a problem could be approached and which issues may be important, but is not expected to provide you with any details about how to solve a specific problem. ***The group need to meet with the supervisor once per week (approximately) to update them of the progress of the Project***. The group need to provide a simple agenda and formal discussions/queries to be raised at the supervisory meeting ***24 hours before the meeting***. In effect, the Process Design Project is driven by the group, and the supervisor is merely acting in advisory capacity.

Group Meetings with Supervisor

You are required to hold a formal group meeting each week at a scheduled time. The purpose of these meetings is raise project related queries with your supervisor, which you cannot answer as a group. The meetings are **not a forum** to resolve detailed technical or engineering issues; these issues should be dealt with separately amongst the group members.

A formal Minute of the meeting must be made and a copied to your supervisor. Your supervisor will chair each meeting, but before you start each meeting you should appoint someone to take the minutes. **These meetings are provided in the Time Table for CPE 407 2016-2017**.

During the course of your meeting you will:

- Record who was present and who was responsible for taking the Minutes
- Read the Minutes of the previous meeting and agree that the record is correct and fairly reflects the decisions and actions arising.
- Individually report on and review the actions set at the previous meeting and you will then collectively establish the degree of progress with the person(s) charged with the responsibility for carrying out specific actions.
- Compare the progress outcomes with the planned outcomes.
- Decide on future actions and objectives, and set deadlines for tasks. Appoint a group member to take Minutes at the next meeting.

Each meeting must result in clear, achievable and quantifiable actions for each member of the team. Vague statements of intent by individuals are not acceptable. The person taking the Minutes will be responsible for typing them up and circulating via email within two days of the meeting cc'd to the supervisor.

Project Progress, Management and Assessment

In order to ensure that each group progress in a timely fashion, the project is already broken down into milestones that you should reach at different points of time. There are three phases that the project needs, to reach different milestones.

The first phase involves information gathering related to process chemistry, regulations, location issues, cost/pricing etc. which is usually called a "scoping" or "feasibility" stage. This will involve a high-level assessment as a group, and define what you will "need" to do in the second stage, and which if the process operations may pose challenges.

In the second phase, each individual within the group will choose a single equipment which they will design. During this period you will need to continue to interact with your group to fulfil the volume sizing and operational requirements for the process to function. This is an individual part of the design.

However, the group's effort will come together as a P&ID which will be tested for its safety of operation. Therefore, **the individual reports and the safety issue should be enclosed in a second group report** where each individual will clearly sign in their contribution, with a common executive summary and P&ID.

Phase 3 of the design revisits the overall sustainability, economics and needs an individual review (or reflection) of the process, which again should be enclosed in a single group report.

The weight of each phase (of the total mark) is also provided against that phase.

Phase 1: 27% of overall mark

Phase 1 relates to the scoping phase of the work. The work is used to develop the feasibility of the process that you will adopt. This will require you to ascertain the process route, determining supplies, regulatory issues surrounding the process at the particular location, and require a preliminary sustainability assessment.

The first set of milestones, which will be reached within 4 weeks, will be:

- Definition of a process route with the associated feasibility issued mentioned above
- Determination the material and energy balances for the production volume, and the supply and transportation systems needed at your location
- Finalization of a process flow diagram (PFD) with full stream definition which shows clearly the materials and energy balances. ○ You have been assigned a supervisor for Phase 1 which is shown below.

Different groups are expected to develop different designs as per the requirements specified here:

Group	Supervisor
1	REDACTED
2	REDACTED
3	REDACTED
4	REDACTED
5	REDACTED
6	REDACTED
7	REDACTED
8	REDACTED
9	REDACTED
10	REDACTED
11	REDACTED
12	REDACTED
13	REDACTED
14	REDACTED
15	REDACTED
16	REDACTED
17	REDACTED
18	REDACTED
19	REDACTED
20	REDACTED
21	REDACTED

This phase runs for the first 4 weeks and ***is assessed via***:

(1) A **group report** and a peer assessment report submitted by each member at the end of **week 4**, and

(2) A **presentation** and viva in **week 4** which is marked by two separate members of staff, one of who will be your supervisor.

The mark breakdown is provided below and the presentation and report (including the peer assessment) each have a weighting of 50% towards the total of phase 1 mark.

Group Report

- Assessed based on group submission of maximum 10 pages – covering ○ Design brief and what is needed to attain the brief **(20%)** ○ Examine – Location and regulations related to process at that location.

  Resourcing of materials/energy availability at that location, Environmental Regulations and issues **(25%)** ○ Initial assessments of process routes and evaluation **– (40%)**

  - Process chemistry and route selection
  - Material and energy balances,
  - Process suppliers and supplies choice
  - Final flow sheet including process streams and specifications
  - Sustainability aspects Initial environmental impact and ethics considerations for sustainability, and how to minimize environmental impact (legal implications?)

  ○ Presentation and style (including language, layout, figures and style) – (**15%)**

Report Style/ Format

- Reports should be no longer than 10 pages of text. An extra 5 pages for figures and tables are allowed.
- Appendices of another 5 pages may be used if needed to provide information on regulations, extra calculations etc.
- Minimum font size is 12, 1.5 line spacing, margin sizes at the top, sides and bottom
- Good English style and grammar required, spell check must be used

Good language, figures and graphing required.

Presentation:

- Presentation of groups will last 30 minutes. The group will then field Q/A from the two staff members for15-20 minutes. It is for the group to decide on how best to present and how to take "expert" question.
- Presentation should cover ○ Brief, including production volume and location which influences process routing and requirement which influences regulatory issues and sustainability criteria **(20)**

○ Material and Energy balances and Final Process Flow Sheet **(30)** ○ Quality of presentation and style **(20)** ○ Ability to take questions from both staff **(30)**

Important Dates for Phase 1

1. Group Report due on **10th February, Friday, 2017 by 4 pm**.
2. Group Presentation on the time tabled hour in Week 4 of semester 2, which is the **week of 6th February 2016**.

Phase 2: Equipment/Unit operations Design 40% of overall mark

The milestones which have to be achieved within the second phase are focused on providing the process units which will allow the process to operate. Each student is expected to design a single unit of the process. Each student should inform the supervisor and their group which unit they are going to design. This has to be a detailed design for each of the unit.

The milestone that has to be attained within the next 4 weeks (i.e. week 8 of the term):

○ Determine the sizing of the unit which will enable the process to operate based on ○ (a) appropriate design equations and ○ (b) appropriate calculations,

In this part of the project you will be working individually, but keeping in touch with your group to discuss any major changes and issues which influence the original flow sheet. In addition, you will continue to meet with your supervisor with the rest of your group to ensure that that the whole group and supervisor are updated on your progress. The supervisor allocated to each group in this phase of the project are listed below.

Group	Supervisor
1	REDACTED
2	REDACTED
3	REDACTED
4	REDACTED
5	REDACTED
6	REDACTED
7	REDACTED
8	REDACTED
9	REDACTED
10	REDACTED
11	REDACTED
12	REDACTED
13	REDACTED
14	REDACTED
15	REDACTED

16	REDACTED
17	REDACTED
18	REDACTED
19	REDACTED
20 (DL)	REDACTED
21 (DL)	REDACTED

In this part of the project, you will be assessed based mostly on an individual report. Notably, there is still 10% of mark allocated to executive summary and P&ID which are group contributions.

The Assessable Outcomes are:

- A full detailed design of a single unit by each student. This should contain
- Description of the unit you are designing, its importance and its dependency or influence on other parts of the process (15%)

Show the rationale and basis of choosing the design equations, and their use in calculations for you to arrive at your equipment and operation specifications **(50%)**

- Make sure you have included the following
- full design equations
- at least one single set of details for calculation, – extra sets can be appended. Programs used (if any) and iterations (optional) should be appended including
- diagrams, figures and graphs used and derived

Description of the aspects for manufacturing, their safety issues, and control elements that are needed for your unit Materials that can be used to manufacture the unit **(15%).**
Make sure you have included

- Materials for manufacture, and the rationale for your choice
- Assessment of safety aspects and risks
- Preliminary control elements that you foresee that are needed in your unit

Report presentation and style **(10%)**

Executive summary (5%)

P&ID of an identified unit which is especially hazardous (5%) – this will be used for your HAZOP activity and is a requirement for that purpose

Report Style/ Format

- Reports should be maximum of 12 pages, and an additional 5 pages for figures and tables.
- An additional appendices of another 5 pages may be used if needed to provide extra information on computer programmes and calculations.

- Minimum font size is 12, 1.5 line spacing, normal (i.e. 2.54 cm) margin sizes at the top, sides and bottom
- Good English style and grammar required, spell check must be used
- Good figures and graphing required
- Report submission: Each individual report should contain the name of the person who worked on that unit. All reports should be collated to form a single report. There should be one executive summary at the front, followed by individual reports of each unit in the order they appear in the process, and the P&ID at the end.
- Only this full report should be submitted on to *Myplace*

Important Dates for Phase 2

1. The full Group report is due on **17th March, Friday, 2017 by 4 pm**.

Phase 3: 33% of overall mark

The third phase of Design involves putting the process together and examining safety during operation and its mitigation including process lay-out design. For this phase you need to come together again as a group. You will look at ensuring the safety of the process during operation and plant lay out. In addition you should also re-assess aspects such as economics of the process and sustainability aspects of the plant. Since these important, but separate aspects can be dealt separately, these milestones have been broken down to activities A and B.

In this phase you will be working with your phase 1 supervisor for guidance.

Group	Supervisor
1	REDACTED
2	REDACTED
3	REDACTED
4	REDACTED
5	REDACTED
6	REDACTED
7	REDACTED
8	REDACTED
9	REDACTED
10	REDACTED
11	REDACTED
12	REDACTED
13	REDACTED
14	REDACTED
15	REDACTED
16	REDACTED
17	REDACTED
18	REDACTED

19	REDACTED
20	REDACTED
21	REDACTED

A. Firstly, the plant/process must be operated safely. This can be achieved by carrying out particular safety analysis – HAZOP. This part is separately **taught and marked by BP by an invited lecturer from BP. (25%)**

1. **The BP lecturer will be delivering a lecture on HAZOP on 13th February 2017, 10-12. Lecture venue will be posted on Myplace.**
2. **During this lecture BP will describe how the group activity has to be performed.**
3. **BP Team will be providing tutorials and activity sessions so that each group will be carrying out an HAZOP using the P&ID developed by the group. *These will be carried out on the week of 13th March 2016.***
4. **BP tutors will assess the groups assigned to them and the mark is returned by BP directly to the module coordinator.**

B. Some hazard can be reduced if the plant layout were appropriate. Show a layout which the group feels is a safe layout of the plant. Discuss the rationale for the layout of the plant. **(15%)**

C. The final phase of the work requires the assessment of the economics of the process and re-checking the environmental impact of the process plant. Reevaluate the process economics and long term sustainability now that you have a more established process plant design. **(30%).**

A **special lecture by Tom Baxter** (Strathclyde Alumni with long industrial experience) on sustainability aspects of Design Project. This will take place on **29th February, 2017**, **10-12 am**.

D. Some of the aspects of safety, economics, and sustainability can improved by better choice of design – including choices of process routes, chemistry, equipment, operations etc. Each ***individual member of the group*** should reflect on the design process, ***and suggest how they can improve the process*** individually **(30%) – individual marks will be awarded on this**

For example, some self-reflection would involve asking yourself if (a) if you had another chance to re-design the unit, what changes would you make and why? (b) How would this be better for the overall process? (c) Would this make it more environmentally friendly? OR if the design team had to work together again, what would you change? For example, if the team did not work then why? How could this have functioned better?

Assessment

- **BP HAZOP activity using the student P&ID is 25% of phase 3**

- **The remaining parts are assessed via a group report which should not exceed 14 pages. This part is work the remaining the remaining 75% of phase 3.**
    - Executive Summary (1 page max)
    - Plant Layout with safety considerations – one page of drawing, and rationale for the layout
    - Process economics with discounted cash flow ○ Environmental Implication: re-visit Sustainability
- **Report Style/ Format**
- Reports should be maximum 12 pages **including individual reflections**
- Minimum font size is 12, 1.5 line spacing, normal margin sizes at the top, sides and bottom
- Good English style and grammar required, spell check must be used
- Good figures and graphing required

Important Dates in Phase 3

BP Lecture: 13th February, 2017

BP Activity Days: Week of 13th March, 2017

Group Report submission date: Friday, 31st March 2017 by 4pm.

A2. Participant Information Sheet and Consent Form

Participant Information Sheet for Interviews

Name of department: Department of Chemical and Process Engineering

Title of the study: The Undergraduate Experience of Engineering Group Design Projects

Researcher

Abdul Wadood Sharif

PhD Student

Contact: abdul.sharif@strath.ac.uk

What is the purpose of this investigation?

It is commonly known that the design project is a distinctive feature of a chemical engineering related degree as per the accreditation from the Institute of Chemical Engineers (IChemE). The design project takes the form of an open-ended problem and requires employment of a breadth of tools acquired throughout the degree, thus simulating work that may be expected from students as they progress into careers.

The purpose of the investigation is to explore the experience of being involved in an undergraduate engineering group design project (current class code CP407/CP408 or equivalent). The study employs an explorative research methodology, called grounded theory, and it specifically aims to identify improvements that can be made to curriculum design and hence benefit engineering education. The research is not trying to prove or disprove hypotheses that have been generated beforehand.

Do you have to take part?

Participation in the investigation is completely voluntary. You have the right to withdraw without detriment and can do so at any time during the study, either in-person or via my contact detail above. If you decide to withdraw from the study, then all associated data will be removed and destroyed. If you decide to withdraw from the study, this will not affect your studies/work in any way.

What will you do in the project?

You are asked to be involved in an unstructured interview on your experience of the group design project which you have been involved in. As the research is exploratory in nature you are asked to discuss as freely as you feel comfortable about your experience in the design project. If you would be happy with audio recording to take place, please tick the corresponding box in the consent form. It is anticipated that the interview process shall not extend an hour in length, however if both the participant and researcher are happy to proceed longer than this the interview can continue longer subject to room availability.

Why have you been invited to take part?

You have been invited to take part as you are or were a student or staff member involved in CP407/408 (or prior equivalent class code) in academic years 2013-2014, 2014-2015, 2015-2016, 2016-2017. No other inclusion criteria were employed.

What are the potential risks to you in taking part?

No risks are anticipated by your involvement, you are not being evaluated in any way whatsoever.

What happens to the information in the project?

All information recorded (in the form of observational field notes as part of this study will be kept strictly confidential and will not be accessed by anyone besides myself, Abdul Wadood Sharif. Only pseudo-anonymised data will be used for publication or for sharing with other researchers (including the chief investigator). Data will be stored in the University of

Strathclyde's secure and encrypted cloud-sharing facility. Data will be stored for the duration of my PhD and the resultant viva process, one year after publication (January 2020). Data will be pseudo-anonymised by changing all names to protect the anonymity of all participants.

The University of Strathclyde is registered with the Information Commissioner's Office who implements the Data Protection Act 1998. All personal data on participants will be processed in accordance with the provisions of the Data Protection Act 1998.

Thank you for reading this information – please ask any questions if you are unsure about what is written here.

What happens next?

If you are happy to participate and have no objections, you will be asked to sign a consent form. Please read this thoroughly prior to signing. I would also like to thank you for participating in the study. You will be sent a short study paper on the outcomes of this research, upon request, once the investigation has been completed. The results of this study are intended for publication with all names changed to protect your anonymity.

Following the interview, you will receive a £10 amazon voucher as reimbursement of your time to participate in the interview.

If you would not like to participate, I would like to thank you for taking time to read this information sheet.

Researcher contact details:
Abdul Wadood Sharif
JW405
James Weir Building
75 Montrose Street
Glasgow
G1 1XJ
Email: abdul.sharif@strath.ac.uk
Tel: REDACTED

Chief Investigator details:
Dr. Ashleigh J. Fletcher
JW405c
James Weir Building
75 Montrose Street
Glasgow
G1 1XJ
Email: ashleigh.fletcher@strath.ac.uk
Tel: REDACTED

This investigation was granted ethical approval by the Chemical and Process Engineering Departmental Ethics Committee.

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Convener of the Departmental Ethics Committee
Department of Chemical and Process Engineering
University of Strathclyde
James Weir Building
75 Montrose Street
Glasgow G1 1XJ
Telephone: 0141 574 5306
Email: contact-chemeng@strath.ac.uk

Consent Form for Interviews

Name of department: Department of Chemical and Process Engineering

Title of the study: The Undergraduate Experience of Engineering Group Design Projects

- I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction.
- I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and without any consequences. If I exercise my right to withdraw and I don't want my data to be used, any data which have been collected from me will be destroyed.
- I understand that I can withdraw from the study any personal data (i.e. data which identify me personally) at any time.
- I understand that anonymised data (i.e. .data which do not identify me personally) cannot be withdrawn once they have been included in the study.
- I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.
- I consent to being a participant in the project.
- I understand that I do not have to answer any questions if I do not feel comfortable.
- I understand that I may be contacted at a later point for further optional involvement in the project (e.g. for follow up interviews) and that I am under no obligation to participate in these if I do not wish to.

(If applicable) I consent to participating in the interview in a café, and accept that the researcher cannot ensure anonymity as the interview is taking place in a public space (please tick) ☐

I consent to being audio recorded as part of the interview (please tick) ☐

(PRINT NAME)	
Signature of Participant:	Date:

A3. Interview Guide

INITIAL QUESTIONS

- So you're coming up to the end of your university degree, how has it been for you?
    - What have been the most positive and negative experiences during your time at university?
- What has been your experience with the different subjects and how you have been taught at university so far?
    - Do you recall if there were any modules you enjoyed?
    - Which modules have you found most useful?
        - What made these modules useful?

INTERMEDIATE QUESTIONS

- Had you had any experiences of project work prior to the GDP?
    - What were these like?
    - How did this/these compare to the GDP?
- Before actually starting the GDP, did you have any ideas or thoughts of what it was going to be like?
    - Do you recall how you felt about it?
- Thinking back to the induction for the GDP in Barony Hall, can you tell me your thoughts and feelings as you learned what the GDP was going to involve?
- As you look back on the GDP, are there any events that stand out in your mind? Can you tell me about this/these event(s)? What about this/these event(s) makes it memorable?
- What did you find challenging about the GDP?
    - What made these challenging?
    - How did you manage these challenges?
    - Would you manage these differently now?
- What was your relationship like with other members of your group?
    - Was it always like this? How did it change?
    - Did you meet up with multiple members of your group ever? What were these meetings like?
- What about your experience of supervisory meetings, what was that like?
    - Do you feel you were involved in these meetings?
- Can you tell me about the ways in which you were assessed?
    - How did you feel about these?
- Could I ask you to describe the most important lessons you learned through your experience of the 4th year GDP?
    - Which of these do you think is relevant for your future career plans?

ENDING QUESTIONS

- Could you tell me about how your views of project work and how you approach it may have changed since completing the GDP?
- After having completed the GDP, what advice would you give the current 4th years who are going to start the GDP next semester?
- Is there something that you might not have thought about before that occurred to you during this interview?
- Is there some else you think I should know to understand the GDP experience better?
- Is there anything you would like to ask me?