# Interdisciplinary Learning in Engineering Practice: An Exploratory Multi-case Study of Engineering for the Life Sciences Projects

THIS THESIS IS SUBMITTED FOR

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### Abstract

Preparing engineering students for interdisciplinary practice in the workplace requires a meaningful understanding of interdisciplinary learning in engineering practice. Such an understanding could help to address the ongoing issues and concerns of the interdisciplinary learning of engineering students. The review of literature on interdisciplinary engineering education raises a major concern of the speculative approach to formulating learning outcomes of interdisciplinary engineering education, which results from the lack of understanding of how practising engineers engage in interdisciplinary learning in their workplaces.

This thesis directly addresses this concern by providing the empirical evidence for a number of learning outcomes, and by identifying the associated learning practices found in three cases of interdisciplinary collaborations between engineers and life science practitioners. It also enhances the understanding of interdisciplinary learning in engineering practice by providing a detailed explanation of why engineers are more likely to engage in those learning practices and how they are more likely to achieve the learning outcomes.

The main contribution of this thesis is in assembling the identified learning outcomes and the associated learning practices into one theoretical framework that embodies both the description and the explanation of interdisciplinary learning in engineering practice for a particular subclass – engineering for the life sciences. The framework describes interdisciplinary learning in terms of four epistemic practices and four learning outcomes. Additionally, it includes a contingent causal explanation for those practices and outcomes by validating the underlying causal relationships.

The findings of this research could inform the formulation of learning outcomes and the deployment of learning practices in interdisciplinary engineering curricular. In addition, the generalisation of the findings to the education domain suggests practices that can help university students in their intellectual development.

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# Preface

Except for commonly understood or accepted ideas, or where specific reference is made, the work reported in this thesis is my own and does not include the outcome of any work done in collaboration. No part of this thesis has been previously submitted to any university for any degree, diploma, or other qualification.

This thesis complies with the Department of Engineering Degree Committee word limit requirement (64771 of a maximum of 65000 words) and the limit on the number of figures (19 figures and 33 tables of a maximum of 150 figures).

Mohd Nazri Mahmud

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# List of Acronyms

ABET	Accreditation Board for Engineering and Technology
AC	Achievement Code
AMBR	Automated Micro Bio-Reactor
ANT	Actor-Network Theory
BNA	Boundary Negotiation Artifact
СЕР	Consultational Epistemic Practice
CPEP	Comparative Epistemic Practice
СРТ	Causal Process Tracing
EEP	Evidential Epistemic Practice
EERN	UK & Ireland Engineering Education Research Network
ID	Interdisciplinary
IEA	International Engineering Alliance
NAE	National Academy of Engineering
OECD	Organisation for Economic Co-operation and Development
PC	Predicament Code
RAEng	Royal Academy of Engineering
REES	Research on Engineering Education Symposium
SEFI	European Society for Engineering Education
SMWT	Self-Managing Work Team
TEP	Translational Epistemic Practice
WEEF	World Engineering Education Forum

# **Chapter 1 Introduction**

#### **1.1** Motivation for the research

The 21<sup>st</sup>-century society is facing many critical challenges that require an interdisciplinary approach for responding to them. Such an approach involves more than one discipline in addressing the problems, issues, or questions associated with those challenges. The complexity of such challenges has been attributed partly to the convergence of distinct technologies originating from different sectors, such as the energy, transportation, health and telecommunication sectors. For example, the interconnection between these sectors by advanced communication technologies is forming an increasingly complex system of interdependent infrastructures; while such a complex socio-technical system enables more efficient service delivery to a wider population, it also requires additional interdisciplinary effort for solving the safety and other issues arising from the exposure of the system to cybercrimes and cyberterrorisms. At the same time, some of the interdisciplinary efforts that seek to address complex challenges are also causing the scale and scope of complex issues to multiply. For example, the interdisciplinary efforts to develop new remedies for degenerative diseases in the synthetic biology and regenerative medicine sectors serve to increase our well-being and longevity, but also contribute to the rising population, aging society, cost of healthcare, and consumption of scarce resources. The scale and scope of these complex challenges are making the 21<sup>st</sup> century society more dependent on interdisciplinary expertise than on the expertise of any individual discipline.

One of the most profound consequences of our increasing dependence on interdisciplinary expertise is the demand for university graduates to be ready for interdisciplinary practice. Such a demand has been growing for several decades. As early as 1972, the Organisation of Economic Cooperation and Development (OECD) advocated the adoption of interdisciplinary teaching and academic restructuring in universities. It defined 'interdisciplinary' as an "adjective that describes the interaction between multiple disciplines" (Apostel *et al.*, 1972;p.25-6). The interaction encompasses simple

communication of ideas and mutual integration of organising concepts, methodologies, procedures, epistemologies, terminologies, and data. Spectacular growth in the number of interdisciplinary degree-granting programs has occurred, at least in the US, over the last quarter of the previous century. Brint *et al.* (2009) reported that the number grew from 674 in 1975/1976 to 1663 in 2000/2001. They categorised 'interdisciplinary programs' as those that draw faculty from more than one academic department. Figure 1.1 shows the growth of interdisciplinary degree programs for nine large interdisciplinary fields according to their survey.



Figure 1.1: Growth of interdisciplinary programs for nine large interdisciplinary fields in the US from 1975 to 2000 (Redrawn based on Brint *et al.* (2009))

The graph shows that towards the end of the last century, the Humanities and the Social Sciences dominated the growth; with the exception of Environmental Studies and Brain, and Biomedical Science, other fields of engineering, physical and natural sciences did not feature prominently in the survey. In recent years, however, the number of interdisciplinary activities as well as of graduate and undergraduate degree programs has been on the rise in engineering, natural sciences and medicine fields (Newell & Gagnon, 2013), and Knight *et al.* (2013) suggest that this marks a shift towards an interdisciplinary approach in higher education.

Interdisciplinary approaches in higher education differ substantially from that of monodisciplinary approaches. In an interdisciplinary approach, the interdisciplinary learners draw on two or more disciplines in order to advance their understanding of a subject or a problem that extends beyond the scope of any single discipline. They integrate and develop information, concepts, methodologies and procedures from two or more disciplines to gain new knowledge, understanding and skills, and commonly also to explain or solve problems (Holley, 2017). Although interdisciplinary approaches had initially emphasised preparation for interdisciplinary practice, their implementation appears to have delivered widespread benefits for learning. It has been shown to result in better student engagement; improved higher-order cognitive skills such as knowledge application, analysis, synthesis and evaluation; greater tolerance for ambiguity; greater sensitivity to ethical issues; reducing disciplinary, political, or religious bias; and more creativity and humility (Holley, 2017; Lattuca et al., 2004; Newell et al., 2001). Many associations were formed, such as the Association for Interdisciplinary Studies (AIS), to promote the adoption of the interdisciplinary approach to universities in order to realise these benefits.

Until the turn of the century, the growth of the ID approach had occurred without any known policy intervention. However, at the beginning of this century, education policy-makers were increasingly concerned about the lack of drive by some critical academic fields in implementing interdisciplinary approaches. As can be seen in Figure 1.1, the fields of engineering, physical and natural sciences were not among those nine fields that were actively offering interdisciplinary degrees. Policy-makers were increasingly concerned about the highly disciplinary structure of undergraduate education in these fields.

Most notably, in engineering, such a concern had led to the US's National Academy of Engineering (NAE)'s bold recommendation in 2005 for all engineering schools in the US to "introduce interdisciplinary learning in the undergraduate environment", stating that "students would benefit from at least cursory learning about the interplay between disciplines embodied in real-world problems" (NAE, 2005;p.55). Similar recommendations emerged in other countries, such as those coming from UK's Royal Academy of Engineering (RAEng) in 2007. Their report on *Educating Engineers for the* 

*21st Century* identified the key future role of engineers as "integrators." Such a role "requires graduates to have awareness and basic skills beyond their traditional discipline boundaries." (King, 2007;p.13). The report advocated the need to embed a multidisciplinary approach in UK undergraduate engineering education.

In recent years, almost all national and international accreditation bodies for undergraduate engineering programs have responded to such policy recommendations by specifying the accreditation criteria for interdisciplinary engineering. ABET criteria 3(d) specifies "ability to function on multidisciplinary teams" (ABET, 2011, 2017) and the IEA specifies "function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings" (IEA, 2015;p.15)." The implementation of interdisciplinary approaches in engineering education continues to spread across the globe as all accredited engineering programs seek to meet the criteria related to interdisciplinary approach.

There have been many implementations of interdisciplinary approaches for engineering education, but there has been little research on interdisciplinary learning to inform them. Research on interdisciplinary learning in engineering education as well as in engineering practice remains scarce for many years (Lattuca et al., 2017; Nersessian & Newstetter, 2014; Spelt et al., 2016; Sutherland Olsen, 2009). Richter and Paretti (2009) characterised the literature they surveyed as mostly focusing on describing experiences in implementing interdisciplinary approaches in engineering curricula with only a few focusing on developing learning outcomes. The literature on interdisciplinary studies has been generally helpful in formulating the outcomes. It conceives interdisciplinarity as a process, the outcome of which is the achievement of integrative synthesis from addressing a problem, question or issue (Klein, 1990; Lattuca et al., 2004; Newell, 1994). In interdisciplinary studies, Klein (1990) and subsequently Newell *et al.* (2001) delineated five key elements of interdisciplinary process: 1) Defining the problem at hand; 2) determining the bodies of knowledge relevant to the problem, 3) developing an integrative framework, 4) evaluating relevant epistemological concepts, and 5) integrating them toward an interdisciplinary understanding or outcome. There is a general agreement among scholars for this general process-oriented framework. However, Newstetter (2011) opined that a general process model without more detail information on the associated learning practices has not been sufficient for informing how to make engineering classrooms more interdisciplinary. According to her, a model of interdisciplinary learning in engineering education should be developed to help us understand how the learning and problem-solving practices from different disciplines interact in addressing real world problems. The deployment of various pedagogical approaches, such as problem-based learning, project-based learning and active learning, in interdisciplinary engineering curricula, has resulted in some successes as reported by Lattuca *et al.* (2011), but resulted in some problems as reported by Richter and Paretti (2009). These mixed results could be indicative of our lack of understanding of how and why learning outcomes are achieved or not.

The lack of understanding on interdisciplinary learning that is sufficient for informing interdisciplinary education has been going on for a long time. Lattuca *et al.* (2004) reiterated the challenge posed twenty years ago by two prominent scholars of interdisciplinary studies, Julie Thompson Klein and William Newell, for researchers to "probe the precise mechanisms through which interdisciplinary study has such widespread effects" (Klein & Newell, 1997;p.411). Lattuca *et al.* (2004) hypothesised the underlying mechanisms for interdisciplinary knowledge acquisition based on the literature on cognition, but their encouragement for researchers to "study it systematically" has yet to be responded (p.44).

There are also derivations of the outcomes of interdisciplinary engineering education based on the literature on interdisciplinary studies such as those derived by Borrego *et al.* (2007), Richter and Paretti (2009) and Lattuca *et al.* (2013). However, Lattuca *et al.* (2012) cautioned that this approach of formulating the outcomes based solely on literature review is 'speculative' (Lattuca *et al.*, 2012;p.12). There is a strong reason to be cautious in speculating learning outcomes. As stated by Newell and Gagnon (2013), in interdisciplinary studies, the outcomes of interdisciplinary activity has so far been characterised as 'comprehensiveness' in understanding the issues, topics, or problems at hand (p.24). However, they urged researchers to revisit such characterisation since they noticed that the locus of interdisciplinary activity has shifted from its origin in the undergraduate teaching of humanities and soft social science subjects to the real world research and applications in natural sciences and medicine. Interdisciplinary practitioners increasingly include non-academics and professionals who are also interested in creating and implementing solutions rather than only in achieving comprehensiveness in understanding. Newell and Gagnon (2013) thus prompted the "need to learn from these professionals". Indeed, interdisciplinary activities in the interstices between health sciences and engineering have been delivering innovative medical devices and technologies to the healthcare market for many years.

More recently, an emerging approach to interdisciplinary curricular design, known as the translational approach, has been used to investigate interdisciplinary activities in a biomedical workplace. Proponents of this approach argue that workplace settings provide more realistic requirements and challenges for interdisciplinary learning than educational settings (Nersessian, 2009; Nersessian & Newstetter, 2014; Newstetter et al., 2010). Nersessian and Newstetter (2014), MacLeod and Nersessian (2016) and Newstetter (2011) have studied interdisciplinary practices in a biomedical engineering research lab in a university. They revealed that the major challenge of interdisciplinary learning in that setting is developing selective, integrated understanding of biological concepts, methods, and materials that are relevant to work goals and problems. This selective, integrated understanding seems to be different from the notion of comprehensive understanding found in interdisciplinary studies literature. However, they suggest "prior knowledge often will not help" the engineers in achieving selective, integrated understanding (MacLeod & Nersessian, 2016;p.7). This suggestion seems to challenge the hypothetical explanation that prior knowledge could be helpful for acquiring knowledge from other disciplines. However, these studies do not identify the learning practices that arise from this challenge. To date, I have yet to find studies that report how practising engineers engage in interdisciplinary learning in industrial settings.

The scarcity of research on interdisciplinary learning in engineering practice and the unresolved questions about outcomes, learning practices, and the underlying mechanisms have important implications for engineering education research. Without sufficient understanding of how interdisciplinary learning is enacted in engineering practice, the engineering education research community has been relying on interdisciplinary studies in the humanities, such as studies by Newell *et al.* (2001), Mansilla and Duraising (2007) and Repko (2008), to speculate the learning outcomes and to develop hypothetical explanation. Although studies related to interdisciplinary practices in educational setting has been growing (Lattuca *et al.*, 2012; Lattuca *et al.*, 2017), there is little empirical evidence from engineering practice to support the formulation of learning outcomes, the identification of learning practices and the explanation of the underlying mechanisms.

Nevertheless, the implication of this introductory background on the topic of interdisciplinary learning is a motivating one for this research. It is motivating to know that interdisciplinary learning in engineering education will continue to be of great significance to our society and industry, and therefore of great concern to many stakeholders. Substantial contributions have been and are being made, and researchable questions have been raised by scholars in interdisciplinary studies and engineering education to the extent that it is timely to complement their contributions with a research on interdisciplinary learning in engineering practice in the industrial workplace. The next sub-section develops the research focus and objectives.

#### **1.2** Focus and objectives of the research

This research is driven by the belief that the development and implementation of interdisciplinary learning in engineering education settings should be sufficiently informed by an evidence-based understanding of the phenomenon of interdisciplinary learning in engineering practice settings. This focus on engineering practice settings would complement the on-going research within the engineering education and industrial laboratory settings.

Within this focus, the objectives of this research are twofold. The first objective is to identify the learning practices that engineers engage in and the corresponding learning outcomes they achieve. The second research objective is to explain why they engage in those practices and how they achieve those outcomes.

#### **1.3 Organisation of the thesis**

This thesis is organised into eight chapters.

This first chapter introduces the motivation of the research, outlines the research objectives, and describes the organisation of the thesis.

The second chapter reviews the literature and identifies the relevant issues that should be addressed within the scope of the research focus and objectives. It also identifies the remaining knowledge gaps that have yet to be addressed by the reviewed literature. These knowledge gaps become the requirements for knowledge.

The third chapter describes how the research is designed to satisfy the knowledge requirements identified in Chapter 2. It provides the configuration of the different aspects of the design by formulating the research questions, determining the philosophical position, developing a conceptual framework, and configuring the research methods.

The fourth chapter then describes the methods of data analysis in detail. It includes the principles for data analysis, and the analytical processes and procedures.

The fifth chapter reports the analyses, results, and findings of the first case study that develops a preliminary theoretical framework.

The sixth chapter then reports the analyses, results, and findings of two further case studies that refine and generalise the preliminary theoretical framework.

Then, the seventh chapter discusses the overall findings from the theoretical and methodological perspectives, and positions the findings within the current bodies of knowledge.

Finally, the eighth chapter assesses the significance of the findings in terms of their contributions to theory and implications for educational practices.

# **Chapter 2 Literature Review**

#### **2.1 Introduction**

This chapter reviews four strands of literature in order to understand how this research might inform interdisciplinary learning in engineering education. Table 2.1 lists the four strands of literature and the rationale for reviewing them.

Strands of literature	Rationale for their review			
Interdisciplinary learning in engineering education	The literature would inform the critical issues related to interdisciplinary learning of engineering students. This helps identify the knowledge required for addressing those issues.			
Theoretical perspectives of learning	This literature is fundamental to the understanding of interdisciplinary learning since it considers many different views of learning. By reviewing this literature, the different views of learning can be assessed to determine their relevance for conceptualising interdisciplinary learning in a way that is useful for engineering education.			
Organisational knowledge and learning	This literature is important since it views organisations as institutions that integrate the specialised knowledge of their members (R. Grant, 1996b). By reviewing it, this research could assess the extent to which the learning practices found in this literature could sufficiently inform interdisciplinary learning in engineering education.			
Engineering practice literature	This literature is necessary to be reviewed since interdisciplinary learning in the workplace occurs in the context of practice rather than in classrooms or training rooms. Additionally, researchers would like to know how engineering knowledge and experiences could be used for interdisciplinary learning.			
Other strands of literature have been explored but not pursued for detailed reviewing:				
<ol> <li>Interdisciplinary studies literature: This literature has been concerned mostly with how interdisciplinary people in the academia - especially in interdisciplinary educational programs – study complex phenomena or problems, such as the problem of acid rain studied by students and scholars of environmental studies. It has yet to be concerned with how non-academic professionals collaborate across disciplines in the workplace context.</li> <li>Cross-disciplinary innovation literature: This literature has been concerned mainly with how organisations, rather than their individual members, learn to integrate knowledge across different industries for producing innovations. Therefore, it focuses more on the organisational policies and practices that foster cross-disciplinary innovation.</li> </ol>				
<ol> <li>Interdisciplinary to interdisciplinary to required such as skills, rather than</li> </ol>	3) Interdisciplinary team science literature: This literature has been concerned mainly with how interdisciplinary teams establish teamwork. Therefore, it focuses more on identifying the skills required such as communication skills, leadership skills, conflict resolutions and negotiation skills, rather than on skills required for dealing with knowledge from different disciplines.			

Table 2.1: Four strands of literature reviewed by this research

The review elaborates issues in interdisciplinary learning in engineering education, and considers how the existing bodies of knowledge could bear on those issues. The outcomes of this consideration include the identification of knowledge gaps, and the implications for this research in terms of how it seeks to address those gaps. This review can be viewed as a process, which is represented visually in Figure 2.1 below.



Figure 2.1: Literature review process for this study

This chapter is organised into eight sections. The first, this section, introduces the purpose, contents, and intended outcomes of the review chapter. The second section clarifies the meaning of the term 'interdisciplinary learning' used in this thesis. Then, the third section reviews studies of interdisciplinary engineering education in order to identify critical issues, which are used to guide the selection of further bodies of knowledge. After that, the fourth section reviews five theoretical perspectives of learning, and assesses the extent of their relevance in understanding different aspects of interdisciplinary learning.

The fifth section reviews the organisational knowledge and learning literature. In doing so, it clarifies the meaning of 'knowledge' used in this thesis, and elaborates on the

different kinds of knowledge, processes, and barriers that might be involved when interdisciplinary learning is undertaken in organisational settings. Then, the sixth section reviews the engineering practice literature in order to identify the different aspects of engineering practice that could be useful for engaging in interdisciplinary learning. Towards the end of the chapter, section seven integrates all the bodies of knowledge that have been reviewed and assesses to what extent such integration could bear on the critical issues. It also identifies remaining gaps in knowledge, elaborates on their implications for this research, and proposes how this research should seek to address those gaps.

Finally, section eight summarises and concludes the findings of the literature review chapter, thus setting the stage for Chapter 3, which describes the research design.

#### 2.2 Definition of 'Interdisciplinary Learning'

The use of the term 'interdisciplinary learning' in this thesis requires clarification. This is due to at least three reasons. The first reason is due to the different understandings of the term used in two different bodies of literature reviewed in this thesis. The second reason is that the meaning of the word 'discipline' embodied in the adjective 'interdisciplinary' needs to be properly understood in relation to the way in which the disciplines are being defined nowadays. The third reason is due to need to differentiate between the adjective 'interdisciplinary' and the other adjectives that are often used interchangeably, such as 'multidisciplinary' and 'transdisciplinary'.

#### 2.2.1 Clarifying the meaning of 'interdisciplinary learning'

There is a potential difference in the understanding of the term 'interdisciplinary learning' when it is used in two different contexts. The first context of usage, which applies to this study, refers to the act of *'learning knowledge of one or more disciplines other than one's own'*, as used by organisational learning scholars who debate about the

extent to which specialists from different disciplines have to learn from each other (R. Grant, 1996b; Majchrzak *et al.*, 2012; Schmickl & Kieser, 2008). On the other hand, the second context of usage, as used in interdisciplinary studies literature, refers to an approach to students' learning and development, which puts students in interdisciplinary settings for developing their readiness for interdisciplinary practice (Borrego & Newswander, 2008; Ivanitskaya *et al.*, 2002; Lattuca & Knight, 2010; Newell & Klein, 1998; Richter & Paretti, 2009). To avoid confusion, this thesis refers to this interdisciplinary approach to learning and development as *interdisciplinary education*, whereas the term *interdisciplinary learning* specifically means learning the knowledge of one or more disciplines other than one's own.

#### 2.2.2 Clarifying the definition of 'discipline'

The need to clarify the meaning of the word 'discipline' arises due to the significant difference between the common understanding of it and the understanding that arises from the way in which the disciplines are defined nowadays.

It is increasingly common, especially among university students, to understand the 'disciplines' as the combinations of courses taken in order to satisfy some requirements, such as the requirements for graduation or professional qualifications (Gardner, 2000). Even scholars of interdisciplinary studies contend that the term 'discipline' signifies "the tools, methods, procedures, exempla, concepts, and theories" (Klein, 1990; p.104), which are the different types of knowledge contents found in course textbooks and training manuals.

However, understanding a particular discipline as a combination of required courses and knowledge contents could be troublesome. Different degrees and training programmes that associate with the same discipline tend to differ, however, in their combinations of required courses and knowledge contents. It is not clear how these differences in courses and knowledge contents could still be affiliated to the same discipline if we define the disciplines in those terms. Moreover, interdisciplinary scholars, such as Julie Thompson Klein, have rightly observed that the tools, methods, procedures, exempla, concepts, and theories keep on changing (Klein, 1990). Nowadays, with a widening involvement of different stakeholders - such as government, employers, and accrediting bodies - in determining what practitioners of some disciplines should do, the change in the required courses and contents are becoming even more frequent and dynamic. Therefore, it seems useful to move away from defining the disciplines in terms of courses and knowledge contents only.

With the increasing interests of many stakeholders on the disciplines, the process of defining the disciplines is becoming more consultative. Through consultation with the stakeholders, the definitive aspects of a given discipline usually emerge from the joint sense making of those involved in the process. Often, this sense making culminates in an agreed set of capabilities that should be possessed by the practitioners of the discipline. Thus, this consultative way of defining the disciplines has fostered the understanding that the disciplines refers to what capabilities the practitioners have, rather than the knowledge they know or the tools they use. Many professional organisations have specified a set of capabilities that define their disciplines (Dowling & Hadgraft, 2012).

An example of such a consultative process is illustrated by the Define Your Discipline (DYD) process developed by Dowling and Hadgraft (2012). The process has been widely used for defining engineering and non-engineering disciplines in Australia. One of the applications involves defining the Environmental Engineering discipline for the purpose of curriculum development and renewal. The authors show how the interests of the Australian government, employers and accrediting bodies - on determining what engineering graduates should be able to do - are eventually translated into a definition of the Environmental Engineering discipline in terms of the capabilities that graduates of the disciplines should have (Dowling & Hadgraft, 2012).

Other relevant aspects of the disciplines are usually subsumed by the capability-based definition. In the same example, the capability-based definition of the Environmental Engineering discipline has been used to consultatively identify the aspects of the discipline that underpin the stated capabilities. Those aspects include a set of tasks that

existing practitioners of the discipline usually perform, the relevant work processes involved, the relevant technical and generic skills and knowledge, and the contexts in which those tasks and work processes are situated. The authors show how the details of the definition have usefully informed the development and renewal of their Environmental Engineering program.

Thus, consistent with the process of defining the disciplines described above, this research clarifies that the word 'discipline' embodied in the adjective 'interdisciplinary' refers to, first and foremost, the capabilities possessed by the practitioners. It therefore follows that the different disciplines, are distinguishable by the capabilities that they have even though they might share some courses and knowledge contents in common.

#### 2.2.3 Clarifying the adjective 'interdisciplinary'

Another potential confusion in the meaning of 'interdisciplinary learning' could come from the adjective 'interdisciplinary'. 'Interdisciplinary' has been used interchangeably with 'multidisciplinary' and, to a lesser extent, with 'cross-disciplinary' and 'transdisciplinary' (Klein, 1990; Lattuca & Knight, 2010). However, scholars are promoting clear distinctions between the adjectives 'interdisciplinary' and 'multidisciplinary' by clarifying the definitions of their corresponding nouns, 'interdisciplinarity' and 'multidisciplinarity'.

For the noun 'interdisciplinarity', different definitions are converging towards the process-centric definition (Borrego & Newswander, 2010; Lattuca & Knight, 2010), which was proposed as follows:

Interdisciplinarity is a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline or profession... [It] draws upon disciplinary perspectives and integrates their insights through construction of a more comprehensive perspective" (Newell & Klein, 1998;p.393-4).

This definition of 'interdisciplinarity' has been clearly contrasted from the noun 'multidisciplinarity', where knowledge integration is not required (Lattuca & Knight, 2010). It should also be worth mentioning that the term 'cross-disciplinarity' encompasses both 'inter'- and 'multi-disciplinarity' (Borrego & Newswander, 2008), whereas 'transdisciplinary' involves merging two or more disciplines to become a hybrid discipline (Nersessian & Newstetter, 2014), such as Mechatronic engineering, which is a hybrid between the Mechanical and Electronic Engineering disciplines.

Based on the process-centric definition of 'interdisciplinarity' stated above, 'interdisciplinary learning' is also a process, which starts with interactions between practitioners or experts who possess different set of capabilities. Since their interactions are often motivated by the value of integrating their underpinning knowledge contents and skills, they often bring their own disciplinary knowledge into those interactions. Interdisciplinary learning that occurs during such interactions has been a subject of ongoing research within the engineering education research community. The next section provides a review of research in this subject area.

# 2.3 Review of interdisciplinary learning in engineering education

The purpose of this review is to identify critical issues related to the interdisciplinary learning of engineering students. The following subsections review five topics identified by different studies of interdisciplinary engineering education.

#### 2.3.1 Formulating learning outcomes of interdisciplinary education

Learning outcomes are statements that specify a set of abilities that students should develop. For interdisciplinary education, educators and researchers have sought to formulate outcomes that align to the workplace requirements for interdisciplinary practice. However, current formulation of outcomes remains "speculative" (Lattuca *et al.*, 2012;p.12) since it relies entirely on reviewing literature from interdisciplinary

studies in the humanities (Borrego & Newswander, 2010), rather than on studying actual workplace practices.

There have been at least three separate sets of speculative learning outcomes borrowed from interdisciplinary studies in humanities such as Newell *et al.* (2001), Repko (2008) and Mansilla and Duraising (2007). The first set proposes that "abilities to synthesize and to evaluate the testimony of experts" are among the necessary learning outcomes (Lattuca *et al.*, 2004). The authors argue that students need to develop the ability to "evaluate and select from among differing perspectives that bear on a problem" and "to resolve conflicting ideas and opinions, and to evaluate evidence supporting or refuting them ... but also commit to a personal perspective" (p.31-5).

Since engineering students are provided with foundational knowledge that crosses many disciplines, rather than trained with specialised knowledge and skills of many different disciplines throughout their studies, the abilities mentioned above indicate a high expectation of engineering students. It is not clear how students would learn to gain the ability to evaluate and select knowledge of other disciplines without learning specialised knowledge of other disciplines. Therefore, Lattuca *et al.* (2004) proposes that "hypothesised routes to learning require systematic study" (p. 44).

Secondly, Borrego *et al.* (2007) derive eight possible learning outcomes based on the Cognitive Flexibility Theory (Spiro *et al.*, 1988), which theorises about the use of flexible cognitive strategies to acquire advanced-stage disciplinary knowledge. The outcomes stipulate that engineering students should be able to (Borrego *et al.*, 2007;p.2):

- define key terms from another discipline that are relevant to an engineering project;
- develop a common vocabulary with collaborators from another discipline;
- describe strategies for learning new content in an unfamiliar discipline;
- compare and contrast research approaches and values from one discipline with those in another;
- enumerate theories or categorizations for describing interdisciplinary interactions;

- select an appropriate approach for organizing an interdisciplinary team project;
- summarise current debates in the value and evaluation of interdisciplinary work;
- coordinate multiple disciplinary viewpoints to help their teams successfully complete a multidisciplinary team project.

Clearly, this set of outcomes covers more than just the ability to learn from different disciplines as it also includes how to organise projects. Parts of those outcomes that relate to interdisciplinary learning include defining terms, and comparing and selecting the approaches of different disciplines. They speculate that "interdisciplinary thinking", which is the "cognitive flexibility to mediate between disciplinary viewpoint" can be developed for learning advanced-stage knowledge if students are exposed to ill-structured problems (Borrego *et al.*, 2007;p.2). However, they did not identify the mechanism by which exposure to ill-structured problems could lead to successful acquisition of knowledge and interdisciplinary thinking ability.

Thirdly, Richter and Paretti (2009) also used literature review to derive a set of outcomes that dictate abilities to:

- identify the contributions of multiple fields to a given complex problem;
- value the contributions of multiple fields;
- identify the information needs and constraints of experts in other disciplines to ensure effective collaboration;
- integrate approaches from multiple fields in a synthetic way;
- learn from both the methods and content of other disciplines to contribute to the project and inform future work.

The three different sets of learning outcomes differ mainly in the different expectation of the ability to evaluate knowledge contributions by experts. This expectation is in the first set but is not shared by the other two sets. It would be useful to address the variations in outcomes by complementing the literature-based formulation with an approach that relies on empirical evidence. Empirical evidence from engineering practice in the workplace may also identify the relevant mechanisms that could lead to successful outcomes.

#### 2.3.2 Using engineering knowledge for interdisciplinary learning

Cognitive theories propose that prior knowledge can be used for learning new knowledge. Lattuca *et al.* (2004) draw on those theories to explain hypothetically that by organising disciplinary knowledge into mental models known as 'schemas', it could then be used to learn knowledge from different disciplines. They hypothesise three mechanisms by which disciplinary knowledge could possibly be used for interdisciplinary learning based on the work of Rumelhart and Norman (1976).

The first mechanism is called 'accretion', which they understood, in the context of interdisciplinary learning, as the accumulating and encoding of conceptual knowledge and information from other disciplines into knowledge structures called 'schemas'. The second one is called 'tuning', which refers to the modification of existing schemas for accommodating more knowledge of different disciplines, rather than simply the addition of more knowledge into the structure. The third one is called 'restructuring', which refers to the construction of new schemas to incorporate more knowledge of different disciplines (Lattuca *et al.*, 2004).

These hypothesised mechanisms are useful for examining how engineering knowledge and skills could be used for interdisciplinary learning. However, there is a lack of evidence from actual cases of interdisciplinary learning to validate their operations and to identify their roles in achieving other speculated learning outcomes, such as evaluating knowledge. Lattuca *et al.* (2004) propose, "hypothesised routes to learning require systematic study" (p. 44). Consequently, there have been a few attempts to study work practices in organisational settings.

#### 2.3.3 Engaging with work practices in organisational settings

Work practices often involve collaboration between people from different functions, departments, and disciplinary background. Recently, engineering education researchers have begun to study some of those practices to propose some learning approaches.

First, McNair *et al.* (2009) introduces the concept of Self-managing Work Teams (SMWT) from studies of industry teams, and examines its usefulness as a pedagogical approach for an interdisciplinary project. In SMWTs, teams are given autonomy to decide on how to proceed with team activities.

This work relates to interdisciplinary learning since it highlights how autonomy could possibly influence learning outcomes. For example, teams that have the autonomy to decide whether they should adopt, avoid or change knowledge of a particular discipline will probably achieve different outcomes compared to teams that only have the mandate to reuse knowledge. Therefore, SMWTs may have the potential to address the issue of achieving outcomes beyond acquisition of knowledge, such as evaluation of knowledge. However, the actual learning practices that arise from giving autonomy are not known.

Secondly, Beddoes *et al.* (2011) borrow the concept of Boundary Negotiation Artefacts (BNA) (Lee, 2005) from the organisational knowledge and learning literature. BNAs are objects used to facilitate negotiation across functional and disciplinary boundaries. They apply the BNA concept to one interdisciplinary graduate research team and find that the concept is useful for facilitating interdisciplinary collaboration. However, it is not clear how it relates to interdisciplinary learning.

This work is valuable because it espouses the socio-material view of learning that has recently been promoted in researching workplace learning (Fenwick *et al.*, 2012, 2014; McMurtry, 2013; McMurtry *et al.*, 2016; Reich *et al.*, 2015), and more recently in studying higher education learning (Acton, 2017; Decuypere & Simons, 2016; Fenwick *et al.*, 2011; Hopwood *et al.*, 2016; Kontopodis & Perret-Clermont, 2016; Zukas & Malcolm, 2017). The socio-material perspective emphasises the importance of both social actors and material artefacts such as drawings, models, and prototypes.

An emerging approach to interdisciplinary curricular design, known as the translational approach, argues that workplace settings provides more realistic requirements and challenges for interdisciplinary learning than educational settings do (Nersessian, 2009; Nersessian & Newstetter, 2014; Newstetter *et al.*, 2010). MacLeod and Nersessian (2016); Nersessian and Newstetter (2014) have all studied interdisciplinary practices in a biomedical engineering research lab. They found that the major challenge of interdisciplinary learning in that setting is developing selective, integrated understanding of biological concepts, methods, and materials that are relevant to their goals and problems. They associated this challenge to their assumption that "prior knowledge often will not help" the engineers (MacLeod & Nersessian, 2016;p.7). However, these studies do not identify the learning practices that arise from this challenge.

A similar study by Sutherland Olsen (2009) explores interdisciplinary learning in a technology development project. They emphasise knowing 'how to learn' from different disciplines. However, the research encompasses only the early stage of technology development. Hence, it did not specify practices that could lead to the achievements of learning outcomes at the end of the project.

Consequently, gaps remain in our understanding of the necessary learning practices, and of how these could help students overcome barriers and achieve learning outcomes.

#### 2.3.4 Identifying barriers to interdisciplinary learning

Many educators believe that through repeated participation in problem-based learning and interdisciplinary teamwork students would be able to benefit from their learning (Stentoft, 2017). However, Richter and Paretti (2009) assert that many engineering students face barriers to learning.

Through a case study of an interdisciplinary course, they discovered that the main barrier to making interdisciplinary connections can be conceptualised as 'disciplinary egocentrism'. The concept refers to a form of cognitive barrier, which encapsulates two themes: 'relatedness' and 'perspective'.

The 'relatedness' theme refers to the failure to make a connection between an engineering discipline and an interdisciplinary topic, while the "perspective" theme refers to the failure to make connection between an engineering discipline and other disciplines. They exemplify that sustainable engineering design is an interdisciplinary topic, the complexity of which requires many other non-engineering disciplines such as business and economics, industrial design and sociology.

However, they are concerned primarily with the outcome of developing understanding, rather than concerned with other outcomes, such as evaluation. As a result, there is lack of knowledge about barriers to these other outcomes. Scholars are generally aware of the relevance of cognitive barriers confronting interdisciplinary practices, but have " struggled to articulate them in any precise or detailed way" (MacLeod, 2016;p.20). Nevertheless, the general recognition of these barriers has led to subsequent research on pedagogical practices as intervention strategies for developing understanding.

#### 2.3.5 Developing intervention strategies for interdisciplinary learning

Interdisciplinary learning in engineering education is challenging due to the difficulties in making connections between disparate disciplines. Thus, intervention through pedagogical practices is necessary. Richter and Paretti (2009) propose some teaching interventions, such as lecturing about the perspectives of different disciplines, and about the use of 'analogy' and 'metaphor' for developing understanding. This proposal derives from a literature review rather than from their own research, so they do not illustrate how 'analogy' and 'metaphor' are actually used.

Subsequently, Lattuca and Knight (2010); Lattuca *et al.* (2011) reported some pedagogical practices that are found to work in some exemplary implementations. The following are some of the main strategies they glean from their case studies:

- provide 'universal' language, particularly Mathematics, and common learning experiences, which can be used across disciplines so that better connections between different disciplines can be facilitated.
- provide introductory engineering or design courses or linking courses thematically to help students see the connections among disciplines.
- use design as the integrative task.

Generally, the work reiterates the importance of providing the context, such as design projects, that could promote interdisciplinary learning. However, the actual learning practices and barriers encountered by the students were not identified. Therefore, specific interventions for overcoming barriers to interdisciplinary learning could not be identified.

#### 2.3.6 Summarising and identifying critical issues

The review of interdisciplinary learning in engineering education was intended to identify critical issues related to interdisciplinary learning that demand further research. Five critical issues outlined below appear to demand further attention because the review reveals that:

- Formulation of learning outcomes continues to be "speculative" as it relies mainly on literature review;
- 2. A number of ways of learning have been considered, but without showing how engineering knowledge could be used for interdisciplinary learning;
- 3. The socio-material learning perspective may be useful for informing interdisciplinary learning;
- Cognitive barriers to making interdisciplinary connections are identified, but barriers to other outcomes, such as evaluation, have yet to be identified;

 Intervention strategies are required to show students how they can successfully engage in interdisciplinary learning and achieve the learning outcomes.

This research selects a number of literature sources that can be brought to bear on the above issues.

Firstly, the theoretical perspective on learning literature is fundamental to the understanding of interdisciplinary learning. This literature considers different views of learning; by reviewing this literature, these views can be assessed to determine how interdisciplinary learning should be conceptualised. For example, if interdisciplinary learning is conceptualised as acquisition and transference of knowledge between disciplines, then the learning outcomes, and the ways of learning and teaching are likely to emphasise knowledge acquisition, rather than other outcomes, such as knowledge evaluation.

Secondly, the organisational knowledge and learning literature is relevant as in this literature organisations are viewed as institutions that integrate the specialised knowledge of their members (R. Grant, 1996b). Therefore, learning practices for integrating knowledge from different disciplines in organisations could be highly valuable in informing interdisciplinary engineering education.

Thirdly, the engineering practice literature is also important because learning in the workplace occurs in the context of practice rather than in classrooms or training rooms. More importantly, researchers would like to know how engineering knowledge and experiences gained through workplace practice could be used for interdisciplinary learning, as stated in the second of the five issues given above.

#### 2.4 Theoretical perspectives on learning

There are many different views of what 'learning' means (Ertmer & Newby, 1993), and these different views emphasise different aspects of learning (Greeno, 1997; Merriam,

2008; Van Merriënboer & De Bruin, 2014). By extension, educators' views of interdisciplinary learning would influence what practices and outcomes they emphasise.

The review will explore: 1) which aspects of interdisciplinary learning would be obvious if a particular perspective were used; 2) which aspects of interdisciplinary learning would be obscured if a perspective were used alone; and 3) what are the potential risks of applying one perspective only or applying it in conjunction with other perspectives.

To explore the above, it is helpful to categorise theoretical perspectives on learning into five categories: 1) Behaviourist, 2) Cognitivist, 3) Constructivist, 4) Socio-cultural, and 5) Socio-material.

#### 2.4.1 The Behaviourist perspective on learning

The behaviourist perspective on learning originates from behaviourism, an approach to psychology that focuses on observable physical actions, rather than on mental actions. Such skill-related learning involves practising to respond correctly to a given stimulus. This requires specifying a stimulus and the correct response, and thereby enabling learners to learn through trial-and-error. Learning ends when erroneous performances have changed to skilful performances. Of course, mental action is involved in learning, but such action could not be observed and used for characterising the learning (Ertmer & Newby, 1993; Greeno, 1997; Jarvis & Watts, 2012).

Based on the above description, the behaviourist perspective is useful for recognising aspects of interdisciplinary learning in which a set of physical actions is acquired from one or more disciplines<sup>1</sup>. However, using the behaviourist perspective alone would not be enough because it would obscure the recognition of other aspects of interdisciplinary

<sup>&</sup>lt;sup>1</sup> Another application of the behaviourist perspective to interdisciplinary learning, but is not part of this research, would be to characterise the process of becoming a more skilful interdisciplinary learner through repeated exposure to interdisciplinary learning environment. Here, the change in behaviour (getting better at performing observable learning actions) can be observed when a learner has become competent in taking an immediate and correct action to learn a new knowledge from different disciplines without any guidance. This characterisation of competence development is not pursued because it is not the ambition of this research. This research concerns with how knowledge is learnt, rather than with how competence in performing interdisciplinary learning is acquired through repeated practices.

learning that might involve acquisition of knowledge rather than skills, for example, acquisition of conceptual knowledge through cognitive processes.

There is also a risk in viewing interdisciplinary learning from the behaviourist perspective, even if it is used in conjunction with other perspectives. An observer might think that all engagement with knowledge of other disciplines would be accompanied by an intention to acquire it, and that the absence of acquisition might be mistakenly considered as a failure. This mistake is risky because some of the proposed learning outcomes of interdisciplinary learning extend beyond knowledge acquisition to include evaluation and selective integration.

Therefore, the relevance of this perspective is rather limited and its use needs to be complemented with other perspectives.

#### 2.4.2 The Cognitivist perspective on learning

The cognitivist perspective views learning as the acquisition of knowledge through mental processes, such as 'thinking' and 'understanding' (Jarvis & Watts, 2012). Knowledge is acquired by using one or more cognitive structures, known as 'schema', or 'schemata'. Schema, and its plural form schemata, is a cognitive psychological concept that represents the way in which knowledge and experiences are organised in human brain (Bourgeois, 2011).

Learning from this perspective involves applying an existing schema to new knowledge so that the knowledge can be organised according to that schema before it is acquired. This suggests that existing knowledge could play a significant role in acquiring new knowledge (Bourgeois, 2011). The word 'acquire' signifies that knowledge is transferred and acquired together with its meaning as intended by the knowledge source. This requires that the knowledge and its intended meaning are specified explicitly and objectively.

Based on the above description, the cognitivist perspective would be useful for recognising the aspects of interdisciplinary learning that involve:

- 1) Mental processes such as 'thinking, 'understanding' and 'reflecting'.
- 2) Acquisition and transference process, rather than other processes, such as evaluation.
- 3) Factual knowledge that can be specified explicitly.
- 4) Use of one's disciplinary knowledge for acquiring knowledge of other disciplines using schema.
- 5) Acquisition of basic as well as advanced-level conceptual knowledge from different disciplines.

However, using the cognitivist perspective alone would not be enough because it would obscure the potential recognition of other aspects of interdisciplinary learning which involve:

- 1) Acquisition of tacit knowledge, which cannot be specified explicitly for schemabased organisation.
- 2) Dealing with ambiguity and the subjectivity of knowledge.
- 3) Alternative pathways to learning for achieving knowledge acquisition, other than those hypothesised by the perspective.
- 4) Alternative outcomes, other than acquisition, for example, evaluation.
- 5) The necessity to re-interpret, translate, adapt, and contextualise the acquired knowledge.

There is also a risk in viewing interdisciplinary learning from the cognitive perspective, even if it is used in conjunction with other perspectives. An observer might mistakenly perceive that:

- 1) All engagements with knowledge (basic or advanced-level) are accompanied by an intention to acquire it.
- Any engagement with knowledge (basic or advanced-level) that does not (intentionally or unintentionally) result in acquisition can be considered a failure to learn.
- 3) All knowledge elements to be acquired are already available at the identified knowledge sources without the possibility that the identified sources are not aware of it, or think that it is not their responsibility to know it. For example, an
engineer who would like to learn from a medical practitioner about how the practitioner would diagnose a disease through a computerised robotic interface, whereas the same diagnosis has always been conducted manually.

Based on the above considerations, the cognitive perspective is very useful, but has its limitations. However, the cognitive way of linking disciplinary knowledge to interdisciplinary learning is of concern to engineering education researchers. Therefore, this perspective needs to be used and complemented with other perspectives.

### 2.4.3 The Constructivist perspective on learning

The constructivist perspective differs fundamentally from the cognitivist perspective that focuses on learning objective and context-free knowledge<sup>2</sup>. The constructivist perspective treats knowledge as subjective and context-dependent, thus emphasises the learning processes that involve construction and contextualisation of knowledge interpretation (Cooperstein & Kocevar-Weidinger, 2004; Ertmer & Newby, 1993).

Essentially, the perspective emphasises making sense of knowledge, rather than making a mental model of it. This is because the concern is with applying knowledge in one or more contexts, but not with storing knowledge in the mind or in documents. For example, knowledge that has been described in a qualitative form using specific terminologies in one context can be described differently in another context using quantitative or visual forms with different terminologies, symbols, or parameter values. Such a change in description is even encouraged because knowledge needs to be contextualised according to the context in which it will be applied, rather than organised according to schema where it will be kept (Ertmer & Newby, 1993). The outcome of this form of learning is the ability to reuse the knowledge in different times with different adaptations, rather than the ability to recall it at different times with the same description, for example by writing it on an examination answer script.

<sup>&</sup>lt;sup>2</sup> There is a cognitive perspective that does not treat all knowledge as objective and context-free. In this study, this perspective is considered as part of the constructivist perspective.

Based on the above description, the constructivist perspective would be useful for recognising aspects of interdisciplinary learning that involve:

- 1) Knowledge that is subjective and context-dependent.
- 2) Sense-making and interpreting for building understanding to compensate for differences in disciplinary and professional background and experiences.
- 3) The use of existing knowledge and experience to interpret and contextualise knowledge.
- 4) Contextualisation, adaptation, and translation of knowledge for the purpose of application, such as converting words description into visual representation.
- 5) Reflection and adjustment based on experience of applying the knowledge.

However, using the constructivist perspective alone would not be enough because it would obscure the potential recognition of other aspects of interdisciplinary learning which involve:

- 1) Knowledge elements that are objective and context-free.
- 2) Acquisition and transference of knowledge without re-interpretation, contextualisation or representation.
- 3) Alternative processes, other than knowledge interpretation, for example, knowledge assessment.
- 4) Ambiguity in knowledge claims that requires making a choice of which knowledge is to be applied to a given context.

There is also a risk in viewing interdisciplinary learning from the constructivist perspective, even if it is used in conjunction with other perspectives. An observer might mistakenly perceive that:

 All attempts to make sense of new knowledge are accompanied by the learner's intention to reinterpret, contextualise, and apply it in different form. Sometimes, the eventual intention could be to ascertain the exact meaning intended by the source by narrating it until the source agreed that his intending meaning is understood accurately.

- 2) Any engagement with knowledge that does not result in the construction of an individual interpretation, contextualisation, adaptation, and application could be considered as a failure to learn.
- All knowledge elements to be contextualised, adapted, or interpreted are already specified at the source.

Based on these considerations, the constructivist perspective is very useful. It can be used to investigate how engineering knowledge is used to contextualise knowledge from other disciplines. However, it needs to be carefully applied and be complemented by other perspectives due to its risks and limitations.

### 2.4.4 The Socio-cultural Perspective on Learning

The socio-cultural perspective focuses on learning that involves participation in one or more communities of people, or so-called 'community of practitioners'. The purpose of such participation is either to develop the competence to become a competent practitioner (Lave & Wenger, 1991), or to gain knowledge about the practice of others (Wenger-Trayner & Wenger-Trayner, 2015). The socio-cultural perspective recognises that not all knowledge in a community-of-practice can be specified for immediate acquisition. Instead, to acquire competence or the knowledge of a community, a learner must socialise with practitioners in that community.

Although the socio-cultural perspective explicitly focuses on the social aspects of learning, it implicitly subsumes some of the behaviourist, cognitivist, and constructivist views of learning (Illeris, 2012). However, unlike in the other three perspectives, explicit guidance is either not always available or sometimes not enough for learning according to the socio-cultural perspective.

However, participative learning for acquiring the competence in another discipline might not be relevant. This is because the primary intention for collaborating with different experts is to integrate knowledge and expertise that are necessarily different. If a specialist seeks to replicate the competence of different disciplines, then his newly acquired competencies would be redundant. As Wenger and Wenger rightly put it "we cannot be competent in all the practices ..., but we can still be knowledgeable about them, their relevance to our practice..." (Wenger-Trayner & Wenger-Trayner, 2015;p.19).

Based on the above consideration, using the socio-cultural perspective would be useful for recognising aspects of interdisciplinary learning that involve:

- Authentic participation in a community of practitioners of different disciplines in order to know about, and understand the relevance of, their knowledge and practices.
- 2) Observing practitioners of different disciplines in action.
- 3) Knowledge elements that are not explicitly specified in a form that can be easily acquired and applied, but rather are implicitly and tacitly embodied in practice and hidden assumptions.
- 4) Knowledge elements that are articulated during informal social interactions

Despite its usefulness and coverage of the aspects that are already considered by the previous three perspectives, there are a number of risks in viewing interdisciplinary learning from the socio-cultural perspective. This is because by paying attention to learning that occurs during social interactions, an observer may neglect aspects of interdisciplinary that involve:

- 1) Processes that cannot easily be observed in social interactions, such as the cognitive learning mechanisms suggested by the cognitivist's perspective.
- Interaction with the material, rather than the social entities, for example, a solitary interaction of an engineer with lab-ware and specimens used by scientists.
- Intentions beyond the need to know about, and understand the relevance of, the knowledge and practices of other disciplines, for example to evaluate, to rectify etc.

Therefore, the socio-cultural perspective needs to be complemented by other perspectives if it is used.

### 2.4.5 The Socio-material perspective on learning

In contrast to the socio-cultural perspective, which views social entities as key to learning, the socio-material perspective insists that both the social (i.e. human) and material (i.e. non-human) entities are equally key. This perspective focuses on the relationships and interactions that a learner may form with the social as well the material entities that make up their learning environment. The learner is assumed to learn during the formation and maintenance of these relationships, as well as during his/her interactions with those entities.

The socio-material perspective maintains that a learner can also learn through his/her solitary interaction with non-human entities, such as protein (Knorr-Cetina, 2008). Some scholars have also considered knowledge artefacts/objects such as visual representations, physical and computer models, as a form of materials that act as intermediaries between entities (e.g. a learner learns about a material through computer models of the material, rather than through a direct solitary interaction with the material itself) (Nerland & Jensen, 2012).

Unlike the socio-cultural perspective, which emphasises learning within a community, the socio-material perspective considers learning can extend beyond the community. Learning is distributed across space and time because the social and material entities with which a learner interacts could come from many different communities. Such distributed interactions are viewed as networks of relations with many different entities, or so-called actor-networks (Fenwick & Edwards, 2010).

This distributed view of learning arises due to the recognition by many scholars that in today's society, knowledge is not only generated by, and embodied in, practitioners within communities, but knowledge is also generated by, and embedded in material things, such as plants, animals, artefacts as well as their representations (i.e. drawings, models etc.). Furthermore, knowledge in its various forms and representatives is also becoming widely circulated around the world and across professional boundaries (Nerland & Jensen, 2012).

The result of such a wide circulation of knowledge is the increase in availability and accessibility of knowledge. However, possible differences in the veracity of knowledge claimed by different sources can also result in ambiguity. Therefore, to learn from encounters with different knowledge from different sources, a learner has to perform some learning actions, known collectively as 'epistemic practices' for processing the knowledge that s/he needs. The socio-material perspective focuses on identifying those epistemic practices, and proposes the relevance of learning through epistemic practices (Fenwick *et al.*, 2012, 2014; Karseth & Nerland, 2007; Nerland & Jensen, 2012, 2014a).

Based on the above considerations, using the socio-material perspective would be useful for recognising aspects of interdisciplinary learning that involve:

- 1) Social as well as material entities from different disciplines.
- 2) The formation and maintenance of relationships across different spaces and times
- 3) Knowledge elements generated by, and embedded in, social and material entities.
- 4) Knowledge from different disciplines that is widely circulated, available, and accessible to a learner, such as visual representations.
- 5) Ambiguity and contradictions in the relevance of knowledge.

Many of these considerations appear to be taken for granted by other perspectives, but appear to be of concern to interdisciplinary learning. Most strikingly, the consideration of the ambiguity of relevance of knowledge relates to the learning outcomes of 'evaluation'. Therefore, the use of the socio-material perspective to characterise interdisciplinary learning would be advantageous. However, the use of other perspectives in conjunction is also advantageous when an understanding of the underlying mechanisms of epistemic practices is required. This is because, the sociomaterial perspective does not mention explicitly the use of existing knowledge for interdisciplinary learning.

### 2.4.6 Summarising and committing to a perspective

The review of theoretical perspectives on learning shows the need to emphasise various possible aspects of interdisciplinary learning. In combination, different perspectives are not contradictory; each focuses on different aspects of learning. While some perspectives provide more breadth in coverage of learning aspects than others, they lack depth in other aspects.

So, to gain both breadth and depth in coverage for understanding interdisciplinary learning, the different perspectives are best deployed in conjunction. However, the socio-material perspective deals with aspects that appear to be overlooked, obscured or implicitly assumed by the other four perspectives. As well as emphasising the solitary and participatory learning through interaction with material entities, it considers the issues of ambiguity and contradiction in relevancy of knowledge. These two important aspects are of concern to interdisciplinary learning as evidenced by the efficacy of the boundary negotiating artefact concept mentioned in Section 2.3.3. Therefore, for this research, the socio-material perspective will be used as the main perspective, and other perspectives will be used to gain a deeper understanding of particular aspects as and when required.

Referring back to issues #1 to #5 in Section 2.3.6, by committing to the socio-material perspective of learning, this review lends support to the idea of learning outcomes that span from knowledge acquisition to knowledge evaluation.

Ambiguity and contradiction in knowledge relevance could be one of the potential barriers in integrating knowledge across disciplines in organisational settings. However, the theoretical perspectives on learning do not address barriers between disciplines. In this respect, literature that deals with knowledge processes and barriers in organisational settings could be useful. Thus, this chapter moves on to review the organisational knowledge and learning literature, where the process of knowledge integration is extensively studied.

# 2.5 Organisational knowledge and learning

Organisational knowledge and learning literature is concerned with how organisations use knowledge in production activities. Central to this concern is the elaboration of what constitutes knowledge, and how organisations keep up with learning to gain and sustain competitive advantage. The following review begins with the definition and classification of knowledge. Then, it proceeds to discuss how learning occurs in organisational settings through knowledge processes and interactions. After that, it discusses barriers to those processes and interactions.

### 2.5.1 Knowledge definition and classification

There are many definitions that equate knowledge to "that which is known" by people through life experiences (Machlup, 1980;p.28). Nonaka uses a definition of knowledge that relates to personal belief, judgment, and commitment. He defines it as "justified true belief" (Nonaka, 1994;p.15). Many of these definitions draw on the argument made by Polanyi (1958) that all knowing is personal. Machlup (1980;p.xiii) considers a broad definition of knowledge as "anything that people think they know," but also considers instances when people communicate what they know to others. In this situation, 'knowledge currently conveyed' is termed as *explicit knowledge*, which is part of *personal knowledge*.

Further, when explicit knowledge is communicated, it can then be codified into written forms such as in books and documents. This is classified as *codified knowledge*<sup>3</sup>. It is considered as an impersonal form of knowledge, because it can be 'separated' geographically and temporally from the person who knows it, for example by storing it in a knowledge repository, and remains available even after its contributor had passed away. Thus, there are two different classes of knowledge for productive activities. In this research, the different classes are classified as *personal knowledge* and *impersonal knowledge*. This distinction is helpful for this research because it wishes to make a clear

<sup>&</sup>lt;sup>3</sup> Much literature equates explicit knowledge owned by a person with codified knowledge.

distinction between knowledge that is embodied by people from knowledge that is embedded in material. This ensures consistency with the socio-material perspective.

For the *personal* class of knowledge, scholars have divided it into three different *types of knowledge:* explicit, implicit, and tacit knowledge. Most literature equates implicit to tacit knowledge (see for example, Nonaka (1994), R. Grant (1996a) and R. Grant (1996b)). However, Bennet and Bennet (2008) differentiate between the two.

The explicit type of knowledge can be readily articulated in words and/or represented visually for others to understand it (R. Grant, 1996a; Nonaka, 1994). On the other hand, the implicit type of knowledge cannot be readily articulated. According to Bennet and Bennet (2008;p.407), the implicit type consists of "knowledge stored in memory of which the individual is not immediately aware, but may be pulled up when triggered." The tacit type of knowledge cannot be expressed in words, such as "a knowing of what decision to make or how to do something that cannot be clearly voiced in a manner such that another person can extract and re-create that knowledge (understanding, meaning, etc.)".

For the *impersonal* class of knowledge, it can exist in either codified or embedded forms. The codified form of knowledge is the explicit type of personal knowledge that has been written and kept in documents such as books. On the other hand, the embedded form of knowledge is the explicit type of knowledge that has been stored or embedded into material things such as drawing, artefacts, tools, equipment, specimens as well as in repositories.

While the above description defines and classifies knowledge, it also elaborates on the replication of the explicit part of personal knowledge into its corresponding impersonal types. However, it does not elaborate on what could happen to the tacit and implicit part of the personal knowledge when different individuals collaborate with each other. Therefore, the knowledge conversion literature that elaborates this situation is reviewed in the next sub-section.

### 2.5.2 Knowledge conversion

Knowledge conversion literature discusses the conversion of knowledge through social interactions. Nonaka (1994) elaborates on four types of social interactions that involve knowledge conversion. Massey and Montoya-Weiss (2006) extend Nonaka's work to include interaction between individuals and knowledge repositories as intermediaries between people.

The first type of social interaction is called 'socialisation'. It involves the transfer of tacit knowledge by one or more individuals, and the acquisition of it by others. Three ways of learning are proposed: 'observation', 'imitation' and 'practice', all of which require 'shared experience' among organisational members (Nonaka, 1994;p.19).

The second type of social interaction is called 'externalisation', which involves the transfer of tacit knowledge of one or more individuals, and the conversion of it into explicit knowledge through collaboration with others. It is a tacit-to-explicit form of knowledge conversion. Three approaches to learning are identified: using 'metaphor', 'analogy' and 'prototype', all of which require "successive rounds of meaningful dialogue" (Nonaka, 1994;p.20). In such a dialogue, different perspectives are communicated. There are tacit assumptions behind those perspectives, which are called "mental models", "schemata", "paradigms", "beliefs, and "viewpoints" (Nonaka, 1994;p.16). Metaphors, analogies and prototypes are used during the successive rounds of dialogue to understand those tacit assumptions and eventually to arrive at the "prototype's specifications", which is the explicit knowledge (Nonaka, 1994;p.21).

The third type of social interaction is called 'combination', which involves the transfer of explicit knowledge between two or more individuals who then combine their knowledge. The learning method is through 'knowledge exchange' during meetings and telephone conversations. Learning actions include sorting, adding, re-categorising, and re-contextualising of explicit knowledge.

The fourth type of social interaction is called 'internalisation'. It involves the transfer of the explicit knowledge of one or more individual, and the adoption of it by one or more

other individuals who apply the knowledge until it is tacitly embodied in them. It is an explicit-to-tacit form of knowledge conversion. The methods of 'trial-and-error', or 'experimentation', or 'learning-by-doing' are proposed.

The identification and elaboration of these four types of social interactions provide useful suggestions of learning methods that could be applicable to interdisciplinary learning. However, it assumes unproblematic achievements of outcomes; such an assumption prevents the identification of possible barriers to learning. It does not consider the possible ambiguity in knowledge relevance to problems either. Moreover, there is little concern about integrating different kinds of knowledge. Since interdisciplinary collaboration also requires knowledge integration, the relevant literature on knowledge integration is reviewed in the next section.

### 2.5.3 Knowledge integration

Knowledge integration is considered as the most important role for organisations – as argued by the knowledge-based view of the firm (Demsetz, 1991; R. Grant, 1996a, 1996b). However, the understanding of knowledge integration tends to differ among scholars (Berggren, 2011). The difference lies in the different approaches they espouse for knowledge integration. In this review, two different concepts of, and approaches to, knowledge integration are examined. Each has different implications for interdisciplinary learning.

#### 2.5.3.1 The knowledge transfer approach to knowledge integration

The knowledge transfer approach to knowledge integration is espoused by the mainstream view of knowledge integration (Berggren, 2011). This view understands knowledge integration as the movement of knowledge from dispersed locations to where it is required inside organisations (Berggren, 2011; Carlile, 2002; Carlile & Rebentisch, 2003). The approach offers a three-stage model of knowledge integration:

acquisition, storage, and retrieval (Carlile & Rebentisch, 2003). Firstly, knowledge is found and acquired from external sources. Then, the acquired knowledge is 'stored' in organisational memory in the form of embodied knowledge of organisational members, but it can also be embedded in repositories. Subsequently, the 'stored' knowledge is then retrieved from organisational memory for integration.

This view does not elaborate on individual learning in detail because it focuses on the intra-and inter-organisational level knowledge transfer. It is assumed that the retrieved knowledge is sufficient and unambiguous enough to be used for integration or for acquiring other new knowledge. Furthermore, the efficacy of the knowledge transfer view is challenged when changes in circumstances result in the inadequacy of some, if not all, of the 'stored' knowledge. Thus, Carlile and Rebentisch (2003) further elaborate on the retrieval part, and add a transformation stage. Hence, the knowledge transformation view of knowledge integration.

### 2.5.3.2 The knowledge transformation view of knowledge integration

The knowledge transformation view of knowledge integration understands knowledge integration as a cycle of transformation of knowledge. As an approach to knowledge integration, it consists of three stages: storage, retrieval, and transformation. Knowledge integration begins with the storage process, whereby knowledge is accumulated through learning and experiencing (i.e. applying knowledge). Accumulated knowledge is thus 'stored' (i.e. embodied) in the experience of individuals, but it can also be embedded in storage medias, and artefacts, and in a particular community of practice (Carlile & Rebentisch, 2003).

Then, the retrieval process starts when a new problem requires integration of knowledge. However, the retrieval process here differs substantially from the knowledge transfer approach to knowledge integration. Here, retrieval involves searching for and assessing relevancy of knowledge (Carlile & Rebentisch, 2003). Since this view assumes that some of the stored knowledge is obsolete due to changes in circumstances, the retrieval process requires searching for new knowledge sources, and the assessment of the relevancy of those knowledge sources to a new problem.

This supports the relevance of the socio-material perspective that argues for the need to assess knowledge. It also lends support to the importance of 'evaluation' as a learning outcome. However, the argument of the obsolescence of stored knowledge seems to imply that existing knowledge is no longer useful for acquiring and assessing knowledge; whereas how existing knowledge is used for that purpose is of concern to educators.

The assessment of relevancy of knowledge is especially challenging not only due to the newness of knowledge sources but also due to the specialised nature of knowledge (Carlile & Rebentisch, 2003). For this reason, specialists who bring in new specialised knowledge are supposed to 'represent' what they know so that specialists from different disciplines can understand and assess its relevance.

At the knowledge transformation stage, knowledge representations are transformed into shared representations, which are then used to assess knowledge. Using shared representations, the "relative merits and costs of different solutions could be compared, trade-offs could be made and agreements reached" (Carlile & Rebentisch, 2003;p.1186). As a result, relevant knowledge can be integrated.

The knowledge transformation view seems to suggest that the collaborative knowledge representation method is one way by which interdisciplinary learning could occur. However, it could not inform how disciplinary knowledge could be useful for interdisciplinary learning. Thus, Carlile and Rebentisch (2003) challenge researchers to understand "the underlying mechanisms for knowledge representation in complex social and technical settings" (p.1193).

From an interdisciplinary learning perspective, this knowledge transformation view of knowledge integration suggests that interdisciplinary learning does not only involve the transference and acquisition of knowledge between different disciplines through its codified form or through the four knowledge conversions (i.e. socialisation, externalisation, combination, and internalisation). Rather, interdisciplinary learning also involves understanding and assessing knowledge through its representatives (i.e. drawings, models, and boundary objects).

The argument for knowledge transformation by Carlile and Rebentisch (2003) is based on the recognition of barriers to knowledge integration when different disciplines collaborate. Barrier to interdisciplinary learning is of interest to engineering education researchers, but only "disciplinary egocentrism" (inability to make interdisciplinary connections) has been discovered so far. A review of barriers found in knowledge integration is therefore provided in the next section.

### 2.5.4 Barriers to knowledge integration

In the organisational knowledge and learning literature, barriers to integrating knowledge within interdisciplinary and cross-functional teams have been widely discussed. Carlile (2002) classifies these barriers into three types: syntactic, semantic, and pragmatic barriers.

### 2.5.4.1 Syntactic Barrier

Carlile (2002) understands the syntactic barrier as differences in specialised terminologies used by people from different functions in an organisation. When specialists from different disciplines or functions collaborate, each specialist tends to use their specialised terms to describe his/her knowledge to others from different disciplines. Others perceive specialised terms as disciplinary jargons, and therefore barriers to understanding knowledge from different disciplines arise.

According to Carlile (2002), syntactic barriers pose a problem to the transfer and acquisition of knowledge between different function, but they can be solved by simply defining the terminologies to others. These are explicit forms of knowledge; their exact meaning can be understood due to the specificity of their definitions. This seems to suggest that when dealing with terminologies and jargon, the pathway to interdisciplinary learning is to codify their definitions.

### 2.5.4.2 Semantic Barrier

Semantic barriers correspond to different interpretations of a similar problem by people from different disciplines or functions. Differences in interpretation can arise due to, at least, two reasons.

The first reason corresponds to the familiarity people have with the meanings of certain common words, which have completely different meanings to others from different disciplines. The meanings can be implicitly associated with particular methods in a discipline. For example, a common word like 'sterility' can be associated with different interpretation because different disciplines may have different ways of sterilising. When similar words are used in common, but their meanings and the corresponding implicit assumptions are not, confusion and misunderstanding result in semantic barriers. In this case, the implicit meanings need to be made explicit. This suggests that when dealing with ambiguity in meaning, the pathway to interdisciplinary learning is to engage in learning actions that can decipher the exact meaning of common words used by other specialists.

The second reason corresponds to the implicit assumptions and mental models that specialists from different disciplines use to interpret and explain a common problem. They may not be fully aware of their implicit assumptions and mental models, even though their causal explanation of problems and solutions are actually underpinned by implicit assumptions. Differences in implicit assumptions and mental models could lead to semantic barriers.

According to Carlile (2002), semantic barriers are harder to handle than syntactic barriers. This is because different interpretations are tied to the assumptions that are implicitly held rather than explicitly discussed. It is due to this reason that Boland and Tenkasi (1995) and Carlile and Rebentisch (2003) argue for the deployment of representation methods, shared methodologies and boundary objects. Implicit assumptions can then be explicitly clarified, compared and contrasted collaboratively towards a resolution (Beckett, 2015; Carlile, 2005; Koskela *et al.*, 2016; Thompson, 2016; Thompson *et al.*, 2017). By depicting and exchanging representations, each

specialist can take the perspectives of others into considerations, for example, the use of a cognitive map to represent implicit assumptions about cause and effects relationships (Boland & Tenkasi, 1995).

This argument seems to reinforce the applicability of the interdisciplinary learning method of representing knowledge of other disciplines, then using the representation to collaboratively understand and evaluate knowledge. However, the mechanisms by which this method work has yet to be explained (Carlile & Rebentisch, 2003), thereby reinforcing the need for developing a mechanism-based explanation for interdisciplinary learning (Lattuca *et al.*, 2004).

### 2.5.4.3 Pragmatic barrier

The third type of barrier, called the pragmatic barrier, corresponds to the differences in practices where individual specialists have invested many resources to develop and master them. They have seen "successes that demonstrate the value of the knowledge developed" (Carlile, 2002;p.446). If different specialists suggest different approaches to practitioners who have been benefitting from their existing approaches, then the latter would not readily agree with such suggestions. Additionally, different specialists may differ in their goals and target achievements. According to Carlile (2002), the pragmatic barrier could also be overcome through representation because it can be used to negotiate and make trade-offs. However, from an interdisciplinary learning perspective, the mechanisms by which knowledge representations could lead to the outcome of replacing existing knowledge and practices of other different disciplines are not known. This further entrenches the need for a mechanism-based explanation.

The review of literature on barriers indicates that in organisational settings, scholars recognise that barriers are not necessarily related to the inherent ability, or the lack of it, of different specialists to understand knowledge and perspectives of other disciplines. Cognitive learning that emphasises conceptual knowledge is not enough to develop understanding and other learning outcomes. The review indicates that ways of learning could depend on the types of barrier encountered, thus providing the need to explain contingent pathways to interdisciplinary learning outcomes.

# 2.5.5 Summarising the review on organisational knowledge and learning

The review of the organisational knowledge and learning literature covers a number of topics that are relevant for informing interdisciplinary learning in engineering education. Firstly, it informs about knowledge and the different types that could be encountered by engineers in organisational settings. It clarifies that knowledge can take two main forms: the personal form and the impersonal form of knowledge. In addition, interdisciplinary learners are likely to deal with different types of personal and impersonal knowledge from different disciplines.

More importantly, this section of the literature review shows that socio-material interactions are prevalent in learning in organisational settings. It elaborates on the knowledge conversion and knowledge integration processes by which interactions with social and material entities provide various learning situations. By reinforcing the socio-material view of learning, the review also clarifies that outcomes of interdisciplinary learning in engineering education should span the wider range of outcomes from acquisition to evaluation, and even to contributing knowledge that could replace the existing knowledge of different disciplines.

In terms of addressing the need to know the mechanisms by which interdisciplinary could occur and how engineering knowledge could be used, this review reveals that such need has not been addressed sufficiently. In fact, the review reinforces the need to understand the underlying mechanisms.

Nevertheless, the review reveals that there are many pathways (i.e. successive combination of learning methods) to achieving learning outcomes, and that those pathways are likely to be contingent upon situations in the learning environment, such as the different barriers in organisational settings. Therefore, it informs engineering education that it is useful for students to diagnose the interdisciplinary situation they face, and then make appropriate judgements of the suitable pathway to follow (i.e. learning actions to take to achieve different outcomes).

In terms of identifying barriers, this part of the review suggests that there are three types of barriers in interdisciplinary work. However, little is known about how the barriers interact with learning practices. Therefore, the review can only partially address many of the critical issues described earlier.

Much of the review covers general organisational settings rather than specific settings where practising engineers work. Therefore, in the next section, the engineering practice literature is reviewed to gain a better understanding of the work practices of engineers so that the socio-material practices and learning aspects can be further recognised. It could perhaps give some ideas of what aspects of engineering practice could be useful for interdisciplinary learning.

# 2.6 Engineering practice

The engineering practice literature mainly seeks to conceptualise what practising engineers actually do at work so that engineering education aligns to the needs of engineering practice. To help inform this education-to-practice alignment, engineering education researchers have been engaging with practising engineers in their workplace to develop models of engineering practice. In this section, two most notable models of engineering practice are reviewed: the Unifying Model by Trevelyan (2009) and the Actor-Network Model by B. Williams and Figueiredo (2013). These two models are chosen as they have been developed mainly through engagement with engineers at work, but also because the models do not narrowly focus on only a few aspects of engineering practice, such as design and problem solving. The models are developed based on the perception of activities carried out by the engineers who participated in the studies. Therefore, they both capture a wide range of practices, allowing this research to investigate which aspects of engineering practice are actually useful for interdisciplinary learning.

### 2.6.1 The Unifying Model of engineering practice

The Unifying Model of engineering practice has been developed by Trevelyan (2009) based on a study of the work practices of engineers in Australia. The model represents engineering practice as an enterprise that provides reliable services to its clients. Figure 2.2 depicts the representation of the Unifying Model. The top-most block represents the service that the engineering enterprise provides, and the other blocks represent different aspects of engineering practice. There are also important aspects of engineering practice that are not represented by blocks, but are represented instead by a 'scaffold' that support those blocks. The 'scaffold' represents formal and informal social interactions performed by the engineers in order to ensure other practices could be performed reliably and efficiently. These social interactions constitute 60% of the engineers' working time.



Figure 2.2: Unifying Model of Engineering Practice (Trevelyan, 2009)

These social interactions are collectively termed 'Technical Coordination', defined as "informally securing willing and conscientious cooperation of other people in technical contexts" (Trevelyan, 2010;p.180). As can be seen in Figure 2.2, some of the aspects of 'Technical Coordination' – such as 'informal expertise sharing' and 'informal negotiations of meanings, terminology' – could be related to interdisciplinary learning.

The remaining 40% of the working time is spent on solitary interaction with material entities, which include interacting with systems and abstract data (calculating, modelling, simulation and data analysis, designing, drawing and creating software codes), and interacting with hardware. Again, this shows the possibility of interacting with material entities for engaging in interdisciplinary learning.

Based on the description of the model, it appears to be valuable for this research. It gives a clearer picture of engineering knowledge and experience that can be brought into an interdisciplinary collaboration. However, without empirical evidence of how engineers practise their interdisciplinary learning, it is hard to know how these aspects of engineering practice help achieve the outcomes of interdisciplinary learning; studies of interdisciplinary practice in an engineering context remain scant (Nersessian & Newstetter, 2014).

Consequently, the developer of the Unifying Model "identified a need for more research into engineering as a sociotechnical process requiring *constant distributed learning* by practitioners in the workplace" (B. Williams & Figueiredo, 2013;p.164). In particular, (Trevelyan, 2013, 2014) found the relevance of 'distributed cognition' in engineering practice. Trevelyan's studies on engineering practice were subsequently extended by B. Williams and Figueiredo (2013), who studied the practices of Portuguese engineers. The extended study culminates in an actor-network model of engineering practice.

### 2.6.2 The Actor-Network model of engineering practice

B. Williams and Figueiredo (2013) characterise engineering practice as a network of human and non-human actors represented by the Actor-Network Model in Figure 2.3.



Figure 2.3: Actor-network model of engineering practice (B. Williams & Figueiredo, 2013)

In this model, an engineer is viewed as an actor who interacts with other actors, thus forming social and material networks with other engineering and non-engineering workers, as well as with instruments and technologies in the workplace. In addition, such interactions extend beyond the immediate workplace, thus forming a distributed network of many actors. This model enhances the Unifying Model because it emphasises the wider distribution of social and material interactions performed by the engineers. It also reinforces the prevalence of the 'Technical Coordination' aspects of engineering practices in the Unifying Model; the 'Technical Coordination' aspects constitute 56% of the working time.

The actor-network model depicts (using different font-sizes) the relative frequencies of six engineering repertoires. 'Technical coordination' is the most frequent repertoire, followed by 'creating', 'career development', 'managing processes', 'checking', and 'professional judgement'.

This model is also helpful for interdisciplinary learning because it shows that engineering practice provides engineers with an immense network of socio-material relationships that could be useful for interdisciplinary learning.

Overall, the main contribution of the review of the engineering practice literature is in demonstrating the wide range of aspects of engineering experience and networked relationships that could be useful for interdisciplinary learning. It supports the choice of viewing interdisciplinary learning in engineering practice through the perspective of the socio-material view of learning. However, it does not satisfy the need to know the mechanisms by which these aspects and relationships could lead to the achievement of outcomes of interdisciplinary learning.

### 2.7 Integrating reviews and identifying gaps

This section describes the conceptual flow development that provides a holistic perspective of all five issues, and assesses how well the existing bodies of knowledge reviewed have addressed them. This assessment allows the identification of gaps in the existing bodies of knowledge.

### 2.7.1 Integration of the reviews

The integration of the literature review considers the five critical issues outlined in Section 2.3.6, and assesses to what extent they have been jointly addressed.

 The first critical issue mentioned in Section 2.3.6 relates to the formulation of learning outcomes, which is still "speculative" because it relies mainly on literature review.

The integration of the reviews clarifies that learning outcomes should specify what engineering students should be able to do in an interdisciplinary collaboration when knowledge from different disciplines is brought into such collaboration. While the review indicates that there are differences in the expected outcomes, the approach to formulating them is similar; it is based on the review of literature on interdisciplinary studies. As a result, the outcomes remain speculative, and thus require empirical underpinning.

The socio-material learning perspective suggests that statements of learning outcomes should be aligned to what engineering professionals actually 'do', or their so-called 'epistemic practices', when they encounter knowledge from different disciplines. The outcomes of those 'epistemic practices' in engineering practice should therefore inform the formulation of learning outcomes in educational settings.

The organisational knowledge and learning literature informs that 'epistemic practices' and the associated learning outcomes are likely to be contingent upon situations. However, how different epistemic practices and learning outcomes are contingent upon situations in interdisciplinary learning has yet to be sufficiently understood.

2. The second critical issue mentioned in Section 2.3.6 relates to understanding how to use engineering knowledge and experience for interdisciplinary learning.

The review indicates that current understanding lacks an explanation of how different ways of learning could help students use their engineering knowledge and skills to achieve learning outcomes.

The socio-material view of interdisciplinary learning indicates that the 'ways of learning' can be conceptualised as 'epistemic practices'. The organisational knowledge and learning literature provides useful suggestions of what these 'epistemic practices' might be, but also highlights that 'epistemic practices' are likely to depend on situations. The literature on engineering practice provides suggestions of the different aspects of engineering practice that could provide useful knowledge and experiences for interdisciplinary learning. However, the integrated literature review still could not provide the knowledge about how different ways of learning could lead to achieving outcomes under various contingencies.

3. The third critical issue mentioned in Section 2.3.6 relates to the socio-material perspective on learning.

Learning theories that educators espouse in teaching can determine how students seek to achieve learning outcomes. The review shows that the use of learning theories that emphasis mere participation in interdisciplinary work tends to obscure the potential of using material objects for facilitating participative learning. The socio-material view and the organisational knowledge integration have shown that when interdisciplinary work is required, there is a need to capitalise on the 'material' side rather than relying solely on the social side. The integrated review highlights the relevance of the learning theories that are based on the socio-material perspective of learning. However, empirical evidence from engineering practice has yet to be produced to support this suggestion. 4. The fourth critical issue mentioned in Section 2.3.6 relates to the identification and understanding of barriers to achieving outcomes beyond knowledge acquisition, such as knowledge evaluation.

Understanding the barriers faced by students is important to help them overcome those barriers. In engineering education, the barrier that has been identified is the inability of students to make connections between engineering and different disciplines. The integrated review clarifies that such a barrier, as well as other barriers, exists in the interdisciplinary workplace. There are also different ways of overcoming them depending on what types of barriers are encountered by practitioners. However, how barriers interact with different ways of learning (i.e. 'epistemic practices) has yet to be understood.

5. The fifth critical issue mentioned in Section 2.3.6 relates to the need for more contributions from studies that engage with practising engineers in order to identify work practices that can inform suitable intervention strategies for achieving learning outcomes.

Information about intervention strategies is valuable for educators in helping students cope with barriers to achieving learning outcomes. The knowledge integration literature indicates that intervention strategies could facilitate the achievement of a range of outcomes including the assessment of knowledge relevance. However, it is also acknowledged that little is known about the mechanisms by which such intervention strategies could lead to outcomes achievement. The literature from organisational settings also indicates that intervention strategies are likely to be contingent upon situations, such as different types of barrier.

The relevance of the socio-material perspective, which anticipates ambiguity in knowledge, indicates that intervention strategies should also target the development of situational judgement in the face of ambiguity in knowledge relevance. However, studies that engage with practising engineers in interdisciplinary practice are scant. Otherwise, different situations and suitable practices could have been identified to inform about situational judgement and suitable intervention strategies.

Based on the arguments above, it seems reasonable to suggest that the five critical issues are only partially addressed by the integration of all the reviewed literature. This indicates that there are gaps in existing knowledge with respect to these issues.

### 2.7.2 Identification of gaps in the literature

The integrated review suggests the following gaps in the literature and the corresponding implications for this research.

- 1. With respect to issue #1 in Section 2.7.1 above, the speculative approach to formulating outcomes has yet to be complemented by empirical research that engages with practising engineers. The implication of this gap for this research is that this research should engage with practising engineers, identify their 'epistemic practices' and their corresponding outcomes
- 2. With respect to issue #2 in Section 2.7.1 above, there is a gap in knowledge about how to use engineering experience and knowledge for interdisciplinary learning. The implication of this gap for this research is that this research should explain how engineering knowledge and skills are actually used for achieving learning outcomes.
- 3. With respect to issue #3 in Section 2.7.1 above, the literature lacks knowledge about how socio-material learning practices are enacted by practising engineers in actual workplaces. The implication of this gap is that this research should employ the socio-material perspective of learning to describe and explain how practising engineers practise their interdisciplinary learning.

- 4. With respect to issue #4 in Section 2.7.1 above, the literature lacks knowledge about how barriers interact with different 'epistemic practices'. The implication of this gap for this research is that it should specify how different barriers relate to the deployment of different epistemic practices and their corresponding outcomes.
- 5. With respect to issue #5 in Section 2.7.1 above, the literature lacks studies that engage with engineers in their workplace in a way that different situations and suitable practices could be identified to inform about situational judgement and suitable intervention strategies. The implication of this gap for this research is that it should engage with practising engineers in order to identify different situations and suitable learning practices. It should then develop contingent generalisations on how different situations could lead to deployment of different epistemic practices and their corresponding outcomes. This allows the elucidation of how situational conditions could be diagnosed for making situational judgement about choices of learning practices. In this way, intervention strategies could focus on whether or not students exercise such situational judgement to choose different ways of learning.

# 2.8 Summarising and concluding the review

This chapter has reviewed four bodies of literatures: the interdisciplinary learning in engineering education literature, the perspectives on learning literature, the organisational knowledge and learning literature, and the engineering practice literature.

The review of interdisciplinary learning in engineering education reveals five emerging issues to be addressed:

 Formulation of learning outcomes for interdisciplinary learning in engineering education;

- Understanding how engineering knowledge and experience are useful for interdisciplinary learning;
- Identification of a suitable perspective on learning for informing teaching and learning in interdisciplinary settings;
- 4) Identification of barriers to interdisciplinary learning in engineering education;
- 5) Identification of intervention strategies for supporting students and educators.

In light of these issues, this chapter has selectively reviewed three strands of literature that could be brought to bear on the above issues. Firstly, five different theoretical perspectives on learning have been reviewed in section 2.4 in order to inform the different ways in which interdisciplinary learning in engineering could be understood. Assessment of their relevance to interdisciplinary learning supports the applicability of the socio-material learning perspective, and the commitment to use it as the main perspective for understanding interdisciplinary learning.

Secondly, a review of the organisational knowledge and learning literature has been undertaken to reveal the different ways in which organisation members learn to integrate specialised knowledge across functions and disciplines. The review reveals wide-ranging types of knowledge, interactions between social and material entities, processes for integrating knowledge, as well the barriers to knowledge integration. These organisational situations identify the likely contingencies in interdisciplinary learning within the organisational setting.

Thirdly, the engineering practice literature has been reviewed to reveal the different aspects of engineering practice and interactions that are undertaken by practising engineers, thus providing information about the likely experience and knowledge that practising engineers could use for interdisciplinary learning.

The integration of all the reviews indicates that the five emerging issues can be addressed only partially by the reviewed bodies of knowledge, and thereby resulting in significant knowledge gaps. To fill these gaps, this research has sought to:

1) identify 'epistemic practices', which refer to what engineering professionals actually 'do' when they encounter knowledge from different disciplines during

interdisciplinary collaboration. In addition, to formulate the relevant learning outcomes, it should identify what engineering professionals achieve as outcomes of their epistemic practices.

- explain the mechanisms by which 'epistemic practices' could use engineering knowledge and skills for achieving learning outcomes.
- 3) apply the socio-material perspective on learning to describe and explain interdisciplinary learning in engineering practice.
- 4) specify how different barriers relate to the deployment of different epistemic practices and their corresponding outcomes.
- 5) develop contingent generalisations on how different situations could lead to deployment of different epistemic practices and their corresponding outcomes.

The above constitute the knowledge requirements that inform the design of this research in the next chapter.

# **Chapter 3 Research Design**

## 3.1 Introduction

A research study needs to be designed according to some specific requirements. For this research, the main design requirements are the knowledge requirements derived from the five knowledge gaps identified in the previous chapter.

The design of a research programme "involves the intersection of philosophy, strategies of inquiry, and specific methods" (Creswell, 1994; 2009;p.5). In addition, the choice of design and research methods need to be justified (Case & Light, 2011). Since there are interactions between the different design aspects, the implementation of the design is reflexive in the sense that the choice of one aspect influences the other design aspects in an iterative manner (Maxwell, 2008). This chapter describes how the design process starts by translating the knowledge requirements into two research questions. The research questions determine the options for the first aspect of the research design – the philosophical position –, which is determined in section 3.3.

After determining a suitable philosophical position, section 3.4 shows how the philosophical position informs the development of a conceptual framework. The conceptual framework determines the option for the second aspect of the research design – the strategy of inquiry.

After determining a suitable research strategy, the remaining sections discuss the configuration of the third aspect of the research design – the research method. Section 3.6 discusses the case study research method and identifies the sub-class of interdisciplinary learning studied.

Finally, the last section 3.7 summarises this chapter by showing the overall design configurations of the different aspects of the research design.

# 3.2 Formulation of the research questions

The design of this research is based on knowledge requirements derived from knowledge gaps identified in the previous chapter. These are the knowledge about:

- 1. Different epistemic practices that practising engineers perform when engaging in interdisciplinary learning, and the outcomes they achieve.
- 2. How engineering knowledge, skills and experiences could be used for interdisciplinary learning.
- 3. The application of the socio-material perspective on learning to understand interdisciplinary learning
- 4. How different barriers relate to the deployment of different epistemic practices and the achievement of outcomes.
- 5. Contingent generalisations of how different situations could lead to the deployment of different epistemic practices and the achievement of outcomes.

To address the above knowledge requirements, two main research questions are formulated as follows:

- Research question 1: How engineers practise their interdisciplinary learning in terms of their engagement in epistemic practices, and their achievements of learning outcomes?
- 2. Research question 2: Why engineers engage in different epistemic practices, and achieve different learning outcomes?

The above research questions require an identification task and an explanatory task. The identification task involves identifying a number of aspects of the phenomenon such as epistemic practices and learning outcomes. The explanatory task involves identifying and explaining a number of causal relationships and the underlying causal mechanisms. Both tasks necessitate philosophical considerations in terms of the nature of existence of those aspects. For example, do the underlying mechanisms exist in reality, or do they merely exist in our thinking? This requires the researcher to state explicitly the philosophical position that he holds about the nature of existence, and about the nature of knowledge.

## 3.3 Determination of a philosophical position

In undertaking research on a phenomenon, two assumptions about the phenomenon are central: assumption about the nature of reality of the phenomenon, or the so-called ontological assumption, and assumption about the nature of knowledge about that reality, or the so-called epistemological assumption. There are 'realist' and 'relativist' ontological assumptions, and 'objectivist' and 'subjectivist' epistemological assumptions (Creswell, 2009; Maxwell, 2012b).

The realist ontology assumes that the existence of different aspects of a phenomenon does not depend on our conceptions about them (Braun & Clarke, 2013; Guba & Lincoln, 1994; Kelly, 2017). Accordingly, a realist ontology would assume that the different aspects of interdisciplinary learning phenomena, such as entities that cause the deployment of epistemic practices and the associated causal processes, really exist in reality, and are not merely conceptions of the researcher and his informants (Maxwell, 2012b). On the contrary, a relativist ontology assumes that the different aspects of a phenomenon are conceptions of those who experience and observe the phenomenon; the nature of their existence depends on people's experience, knowledge and the meanings they assigned to them (Harré & Krausz, 1996; Maxwell, 2012b; Schraw & Olafson, 2008).

In considering the choice of epistemological assumptions, there are 'objectivist' and 'subjectivist' epistemologies (Coe *et al.*, 2017; Usher, 1996). Objectivist epistemology assumes that the nature of knowledge about the different aspects of a phenomenon is objective. Such knowledge does not consist of the different interpretations and constructions of people who experience or observe the phenomenon (Allison & Pomeroy, 2000; Cohen *et al.*, 2013). On the other hand, a subjectivist epistemology assumes that the nature of knowledge about the different aspects of a phenomenon is

subjective in the sense that there are different conceptions of the same phenomenon (Cohen *et al.*, 2013; Maxwell, 2012b).

To determine a suitable philosophical position, this research considers three main philosophical positions that differ in their combinations of ontological and epistemological assumptions. Table 3.1 represents their relative positions and assumptions.

		Epistemological assumptions	
		Objectivist epistemology	Subjectivist epistemology
Ontological assumptions	Realist ontology	Positivism	Critical Realism
	Relativist ontology	-	Interpretivism

Table 3.1: Philosophical positions

First, there is a positivist philosophical position, which combines a realist ontology with an objectivist epistemology. According to Alvesson and Sköldberg (2009;p.17), the position claims that "data about the phenomenon being studied are something that already exists out there to be gathered, observed or measured by a researcher". Thus, its objectivist epistemology emphasises the production of objective knowledge in the form of statements about the relationships between observable, or measurable, aspects. Such statements are said to be universal in the sense that they are applicable across different contexts (Alvesson & Sköldberg, 2009; Cohen *et al.*, 2013).

Second, there is an interpretivist philosophical position, which combines a relativist ontology with a subjectivist epistemology. It contends that data about a phenomenon is constructed during research (Alvesson & Sköldberg, 2009); p.23). Such a construction of data could happen when researchers interact with the phenomenon, either directly, such as by taking part in the phenomenon, or indirectly, such as by interviewing those who experience it. Thus, a researcher who takes an interpretivist position would focus

on developing knowledge about the different subjective meanings and conceptions of a phenomenon according to those who experience it (Alvesson & Sköldberg, 2009).

Third, there is a critical realist philosophical position that combines a realist ontology with a subjectivist epistemology (Bhaskar, 1975; Maxwell, 2012b). Critical realism rejects a positivist's claim that objective reality is always accessible for observation and measurement. Therefore, critical realism's realist ontology also includes the identification of aspects that cannot be observed or measured, but are significant for the study, such as the underlying causal processes. Since they are not observable to the researcher, his/her knowledge about them necessarily consists of conceptions. However, critical realism does not endorse multiple realities (Maxwell, 2012b), and thus seeks to develop conceptions that correspond closely to a reality. Therefore, the critical realism philosophy also evaluates the plausibility of different conceptions in terms of how closely they correspond to the actual reality (Edgley *et al.*, 2016; Maxwell, 2004, 2012b; Scott, 2005; Zachariadis *et al.*, 2013).

Critical realism conceptualises about a phenomenon by developing knowledge about contingent and contextual generalisations of the causal relationships between different aspects of a phenomenon. Such knowledge provides a causal explanation of how events and outcomes of a phenomenon could be caused by real entities that may not always be observable or measurable (Maxwell, 2012b). Such contingent and contextualised knowledge of a phenomenon is also known as 'middle-range theory', a type of theory that falls between universal law-like generalisation and detailed contextualised descriptions (Bygstad et al., 2015; Maxwell, 2004; Smith, 2012).

By comparing the suitability of the three philosophical positions, a critical realist position appears to be the most suitable for this research. This is mainly because the researcher recognises that there are limitations in the accessibility, observability, and measurability of the different aspects that this research seeks to identify and explain. Events that have occurred in the past - such as past engagement in epistemic practices are no longer observable. Their real existence in the past does not depend on the researcher's conception. However, the knowledge about them is subjective because the construction of it depends on the conceptions of the informants and the researcher. The prevalence of unobservable aspects in interdisciplinary learning also indicates that data collection needs to rely heavily on retrospective accounts of, and subjective interpretations by, different people including the researcher and his informants. When different interpretations point to competing explanations, their plausibility needs to be evaluated in terms of how closely they correspond to what has actually happened.

Last but not the least, critical realism emphasises the development of knowledge in the form of contingent and contextual causal explanation. This informs the development of a conceptual framework.

### 3.4 Development of a conceptual framework

A conceptual framework consists of the concepts and relationships that represent a general conceptualisation of the phenomenon being researched. It embodies "the main things to be studied – the key factors, constructs or variables – and the presumed relationships between them" (Miles & Huberman, 1994;p.18). The presumed relationships between concepts constitute a tentative "theory about what is going on, what is happening and why" (Maxwell, 2008; p.222-3; Robson, 2002;p.63).

In developing a conceptual framework, this research combines findings from the literature review with the philosophical ideas of critical realism. The literature review suggests that interdisciplinary learning can be viewed as a process. Logically therefore, the conceptual framework is also structured as a process. Critical realism's idea – of contingent causal relationships between different aspects of a phenomenon – is used to inform the construction of a causal structure for the conceptual framework. Thus, the conceptual framework is structured into three sequential stages as depicted in Figure 3.1 below.

As seen in Figure 3.1, the first part of the conceptual framework represents the 'initiation' stage of interdisciplinary learning in engineering practice. Two causal entities that are of interest to this research, interdisciplinary collaboration, and engineering practice, make up this stage. The initiation of the process mainly involves interactions between engineers and other social and material elements within both entities. Such

interactions are assumed to cause the emergence of situations, and the formation of judgements. The two arrows in Figure 3.1 represent the causal links between both causal entities to situations and judgments.



Figure 3.1: Conceptual framework of interdisciplinary learning in engineering practice

The second stage corresponds to events that include the various situations that demand action to be taken on knowledge from different disciplines, judgements that are formed by engineers, epistemic practices that are deployed based on their situational judgments, and the outcomes of those practices. In Figure 3.1, the interactions between 'situations', 'judgments', and 'epistemic practices' components are represented by the three-way arrow that links them. This second stage is called the 'commitment' stage in order to signify that at this stage engineers make a commitment to engage in learning through epistemic practices, according to the socio-material perspective on learning.

Finally, the last stage corresponds to the empirical ontological domain. At this stage, outcomes of engagement in epistemic practices produce empirical traces that can be gathered by the researcher. Demonstration of learning outcomes, such as showing understanding of conceptual knowledge, is the main empirical aspect that is of special
interest to this research. Other empirical traces of events, such as archived materials, are also part of this stage.

The conceptual framework is a generic model that is still lacking in the identification of conceptual categories. Therefore, its further development into a theoretical model requires a research inquiry into the actual phenomenon. Consequently, a suitable strategy of inquiry needs to be selected.

## 3.5 Selection of the research strategy

Research strategy determines how the phenomenon of interest should be examined in order to develop knowledge about its different aspects. Creswell (2003) emphasises that a research strategy "provides specific direction for procedures in a research design" (p.13), and identifies three types of strategies of inquiry: quantitative, qualitative, and mixed-method research strategies.

Among the three strategies, the qualitative strategy is the most optimal choice for inquiring about the different aspects of interdisciplinary learning. This is mainly due to the need to rely heavily on qualitative accounts of events, outcomes, and the entities that cause them. In addition, qualitative strategy would facilitate a deeper understanding of the relevant contexts, situations, and interactions to enable the development of causal explanation (Maxwell, 2004, 2012a, 2016a). Such a use of qualitative strategy of inquiry entails configuring the different aspects of a qualitative research method.

## 3.6 Configuration of a qualitative research method

Research methods offer systematic means for inquiring about different aspects of a phenomenon. Unlike other methods, the case study research method offers a systematic means for addressing 'how' and 'why' research questions (Yin, 2003), and is suitable for developing causal explanation (George & Bennett, 2005; Maxwell, 2004, 2012a). This is

mainly due to its explicit emphasis on the contextual factors that influence a phenomenon.

Further, for developing contingent generalisations, it is important that the 'class' of the phenomenon to be investigated is not defined too broadly (George & Bennett, 2005; Yin, 2003). Therefore, one of the important aspects of designing a case study research method involves focusing on a particular sub-class of a phenomenon.

## 3.6.1 Identification of the sub-class of interdisciplinary learning

Interdisciplinary learning in engineering practice broadly encompasses learning knowledge from many different disciplines. However, this research focuses on a particular sub-class of interdisciplinary learning in engineering practice, where engineers learn:

- 1) Knowledge of the life sciences discipline,
- 2) In the context of their involvement in development projects that integrate engineering and the life sciences.
- 3) To address problems, opportunities, and issues that arise in the life sciences domain.

This sub-class in termed the 'engineering for the life sciences' (Niemeyer, 2017). The main reason for choosing this sub-class of interdisciplinary learning of life sciences knowledge, rather than that of other disciplines, is due to the recent emergence and growth of new industries in which engineering and the life sciences converge, such as Synthetic Biology, Regenerative Medicine, and Bio-Nanotechnology industries. Engineers in these emerging industries need to work in the interstices between engineering and the life sciences for solving problems in the life sciences domain, such as health problems. This demand has led to the creation of many interdisciplinary educational programmes that seek to prepare engineering graduates for interdisciplinary practice in the era of convergence.

Having selected the sub-class, the type of case study design can then be selected.

## 3.6.2 Selecting the type of case study design

Since this research seeks to develop a theory for the chosen sub-class, a multiple-case design is necessary to ascertain the extent to which the theory can be generalised across cases that are representative of the sub-class.

Consistent with the main research question of 'how engineers practise their interdisciplinary learning in terms of their engagement in different epistemic practices, and their achievements of the corresponding learning outcomes?', this research focuses on 'practices' as the unit of analysis as suggested by practice-based studies of workplace and professional learning (Reich *et al.*, 2015). According to Reich *et al.* (2015;p.3), "practices provide units of analysis that bring together the practitioner, the material objects with which they work, their relations with others and the context in which they operate."

In order to provide the necessary variation in the practices of the engineers, purposive sampling is used based on the following variations in experience level as shown in Table 3.2 below.

		Experience in life science domain		
		Low	High	
Experience in engineering practice domain	High	'Experienced engineers'	'Experienced interdisciplinary engineers'	
	Low	'Early career engineers'	'Early career interdisciplinary engineers'	

Table 2.2.	Variation in	lorral	formariance	of prostiging	anginaana
Table 5.2:	variation m	level u	n experience	of bracusing	engineers

Categorising practising engineers as either 'early career' or 'experienced' engineers requires an informed decision on how to differentiate between the two categories. One useful way to inform this decision is to clarify what the term 'early career' signifies. In engineering education literature, the term 'early career engineers' is increasingly common, but to date there is a lack of consensus on what the 'early career' phrase signifies. Much literature has signified the phrase in terms of variables related to age range and the duration of working experiences (Danielson et al., 2011; Greenhaus et al., 2009; Kirkpatrick et al., 2012). However, relating the term to some variables has resulted in contradictory definitions. Therefore, this research has sought to formulate a definition that embodies the common characteristics of the 'early career engineers' as informed by the career development literature.

The concept of 'early career' was first used by Donald Super to refer to 'men who are not yet established' (Super, 1963). He associated them with the early career stage called the 'trial period' during which they try to establish themselves in their chosen careers. The 'trial period' often involves changes in jobs in order to find the most suitable one (Super & Jordaan, 1973). Once found, efforts are made to establish the necessary work habits for performance and promotion. Promotion, within the same organisation or outside, ends the 'trial' or the early career stage (Savickas, 2001).

The applicability of the 'early career' phrase for junior level engineers has been substantiated by the research on the career development experiences of 380 professional engineers and scientists by Hall and Mansfield (1975). Their findings suggest some common characteristics of the early career engineers. They have low seniority, but high need for establishment and advancement, and high tendency to change employers (Hall & Mansfield, 1975).

By taking the career development perspective, the 'early career engineers' in this research is defined as: the newly employed or reemployed engineers who occupy the junior level posts, and have yet to make their first career progression to the senior level posts inside or outside the employing organisations. By default, those who have made a career progression beyond the junior level posts are classified as 'experienced engineers'.

In Table 3.2, the phrase 'experienced engineers' refers to engineers who have progressed beyond the junior level position, and thus have relatively high experience

practising in the engineering practice domain. However, they have low experience practising in the life science domain.

Engineers categorised as 'early career engineers' have relatively low experience practising in both domains in addition to occupying junior-level posts. In contrast, engineers categorised as 'experienced interdisciplinary engineers' have high experience practising in both domain in addition to occupying senior-level posts. Engineers categorised as 'early career interdisciplinary engineers' have high experience practising in interdisciplinary engineering for the life science project but low experience in engineering practice

## 3.6.3 Sampling the development projects within the sub-class

Based on the chosen sub-class of "engineering for the life sciences", this research searched for the relevant development projects and studied five such projects. Table 3.3 lists the projects and the number of informants.

Proj	ects	Number of informants			
		Engineers	Non-engineers	Total	
1	Design and development of a cell-culture automation system	Two experienced engineers	One Biochemist team member	3	
2	Design and development of an automated micro-scale bio- reactor	Two experienced interdisciplinary engineers One early career engineer Head of Engineering Department Chief Technology Officer	One Geneticist team member Chief Executive Officer	7	
3.	Design and development of a cryopreservation system	1 experienced engineer	Chief Executive Officer (with Biology background)	2	
4.	Design and development of a non-contact-based respiratory	1 experienced interdisciplinary engineer	Chief Medical Officer	5	

Γable 3.3: List of projects and informants
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	diagnostic equipment	1 early career interdisciplinary engineer	Chief Executive Officer Founder	
5.	Design and development of an organ perfusion system	Three experienced interdisciplinary engineer	Chief Executive Officer One Senior Consultant with Natural Science background One Senior Design Consultant	6
	All projects	13 engineers	10 non-engineers	23

The academic and professional backgrounds as well as the experiences of the informants are reported in detailed along with the relevant findings in chapters 5 and 6.

The data from the projects are processed according to the analytical methods described in the next chapter: the Analytical Methods chapter.

This section completes the configuration of the different aspects of the research design. The next section provides a summary of the overall design configurations.

## 3.7 Summary of the research design

This chapter has described how the three main aspects of research design – the philosophical position, the research strategy, and methods – are configured. It also shows that the implementation of the research design is a reflexive process where the different design aspects mutually influences each other during the project (Maxwell, 2008).

Firstly, the need to take a particular philosophical position is shown to arise mainly from the formulation of the research questions stated in section 3.2. The questions require the identification and explanation of entities that cannot be observed, or measured. Thus, the critical realist philosophical position is chosen. This choice supports the ontological assumption of the researcher that those entities exist in reality, and that their existence is independent of the researcher's conception of them (a realist ontology). It also supports the epistemological assumption of the researcher that the knowledge about them is necessarily a subjective conception of the researcher (a subjectivist epistemology). By choosing critical realism as the philosophical position, this research commits to evaluate the plausibility of different conceptions in terms of how closely they correspond to the unobserved reality. Critical realism's philosophical position informs the development of the conceptual framework in section 3.4.

Secondly, the need for choosing a particular strategy of inquiry has been shown to arise from the conceptual framework. Its general and high-level state requires a particular research strategy that can obtain empirical data to be used for developing it further into a theoretical framework. The qualitative research strategy has been chosen mainly due to the need to rely on qualitative accounts of events, outcomes, and the entities that cause them.

Thirdly, the need for choosing specific methods has been shown to arise from the need to execute qualitative research in a systematic fashion. The case study research method has been chosen mainly because it offers systematic means for addressing 'how' and 'why' research questions, and it is suitable for developing causal explanation. The choice of case study as a research method entails the specification of a particular sub-class, case-study design, and units of analysis in section 3.6. This choice of the critical realist case study method requires the methods for data analysis described in the next chapter.

## **Chapter 4 Analytical Methods**

## 4.1 Introduction

This chapter is concerned with describing how this research employs a combination of rigorous analytical methods for analysing the case study data.

This chapter is organised into five main sections. After this introductory section, the second section elaborates on the principles of data analysis according to critical realism philosophy. Then, the third section selects and justifies a combination of seven analytical methods. Its seven sub-sections each describes how the individual methods are applied.

Having completed the description of all the seven methods, the penultimate section four identifies four criteria for evaluating research quality and rigour in qualitative critical realist case studies, and discusses how the seven methods contribute towards the attainment of quality and rigour for this research.

Finally, the last section summarises key analytical aspects of this research and leads to the presentation of the data analysis and findings for the first case study in the next chapter.

## 4.2 Methodological principles for data analysis

The analysis of case study data in this research adheres to the five principles of data analysis according to critical realism philosophy as offered by Wynn and Williams (2012). The principles do not recommend specific methods, but identify essential elements of analysis. The following subsections elaborate the five principles and the essential elements of analysis.

#### 4.2.1 Principle #1: Explication of events

The principle of explication of events emphasises the identification of the important aspects of those events that characterise the phenomenon being studied (C. Williams & Karahanna, 2013). In line with the objectives of this research, two focal events characterise the interdisciplinary learning of practising engineers.

- 1. Focal event #1: Engagements in epistemic practices
- 2. Focal event #2: Achievements of learning outcomes

The essential elements of analysis for this first principle include "the abstraction of experiences" from the qualitative interview data (Wynn & Williams, 2012;p.797). Experiences "should include key actions and outcomes' (p. 798). Thus, abstraction of experiences entails translating the concrete descriptions of actions and outcome achievements into abstract concepts and the patterns of relationships between them. Therefore, the researcher needs to abstract key actions and outcomes in terms of theoretical variables and statements of causal relationships between them. Such abstraction "may take the form of an aggregation of minute actions to highlight higher level factors, a reinterpretation to expose structural elements or causal factors, or a reframing through the lens of existing theory." (p. 798).

#### 4.2.2 Principle #2: Explication of structure and context

The principle of explication of structure and context emphasises the need to "identify and analytically resolve the components of the structure that are causally relevant." It also emphasises "describing causal tendencies that generate events" and "understanding the source of these tendencies" and "contextual conditions that influence events" (Wynn & Williams, 2012;p.798). For this research, the two main structured entities are interdisciplinary collaboration and engineering practice, each has their own constitutive components in the form of social and material elements.

Essential elements of analysis in this second principle include (Wynn & Williams, 2012):

- Decomposing the entities into their constituent elements
- Identifying the influential interactions between those elements
- Redescribing those elements and their mutual interactions according to existing theories and frameworks to help conceptualise influential factors

## 4.2.3 Principle #3: Retroduction of mechanisms

The principle of retroduction of mechanisms involves postulating a number of relevant causal mechanisms by which structured entities and the interaction among their elements lead to the occurrence of events (Wynn & Williams, 2012). The postulation of causal mechanisms are necessarily retroductive, rather than deductive or inductive, since the intervening causal processes that underlie a phenomenon are typically unobservable. The essential element of retroductive analysis involves "theorising regarding the existence of any entities not represented in the empirical data" (Wynn & Williams, 2012;p.800).

## 4.2.4 Principle #4: Empirical corroboration

The principle of empirical corroboration emphasises substantiating the causal inferences with the available empirical evidence. This evidence-based substantiation is to "ensure that the proposed mechanisms adequately represent reality, and have both sufficient causal depth<sup>4</sup> and better explanatory power than alternative explanations" (Wynn & Williams, 2012;p.810).

The essential element of this analysis is validation, which "includes the empirical search for either the mechanism itself or its effects." The researcher can "identify other events that should have occurred, related to focal events....using existing data or seek out new data within the current case context "(Wynn & Williams, 2012;p.801).

<sup>&</sup>lt;sup>4</sup> Causal depth refers to the status of a proposed causal entity that is necessary and sufficient to cause a particular outcome. (See George & Bennett, 2005;p.185-6)

Another essential element of corroboration is demonstrating the efficacy of the logic of the causal explanation. According to C. Williams and Karahanna (2013), part of demonstrating the efficacy of the logic involves "detailing how the proposed mechanisms bring about observed outcomes" (p.955). This can be done by providing a causal explanation that consists of a chain of cause-and-effect relationships, or so-called causal links (George & Bennett, 2005).

## 4.2.5 Principle #5: Triangulation of methods

The fifth principle, the triangulation of methods, involves combining multiple approaches to support causal analysis based on variety of data types and sources, analytical methods, and theoretical perspectives. For case study research, a key concern is methodological triangulation to capitalise on the strengths of each method while compensating for their various weaknesses (C. Williams & Karahanna, 2013). This principle signifies the importance of combining several analytical methods in a complementary way.

## 4.3 Analytical methods, process and procedures

Seven analytical methods are combined and organised as the following series of seven analytical procedures:

1) Coding the qualitative interview data using three coding techniques

2) Framing the data and describing influential interactions using the ANTanalytical framework

- 3) Delineating different causal patterns using the typology analysis
- 4) Generating logical causal inferences using the comparative method
- 5) Evaluating the causal inferences using the congruence method

6) Validating causal inferences using the causal process tracing method

7) Generalising causal explanation across the chosen sub-class using the crosscase comparison method

Figure 4.1 shows the analytical process that consists of seven procedures and the corresponding seven analytical methods. The following seven sections 4.3.1 to 4.3.7 describe each of the seven methods and demonstrate how they are employed.



Figure 4.1 Analytical process, procedures, and methods

## 4.3.1 Analytical method #1: Coding

Three coding techniques are identified from Saldaña (2012): Action Coding, Causation Coding, and Pattern Coding.

Action coding helps the researcher to locate and select data segments that contain actions. It is particularly appropriate for locating "on-going action/interaction/emotion taken in response to situations, or problems, often with the purpose of reaching a goal or handling a problem (Corbin & Strauss, 2008;pp.96-7) quoted in Saldaña (2012;p.96). Causation coding enables the researcher to "locate, extract, and/or infer causal beliefs from qualitative data" (Saldaña, 2012;p.163). It is therefore suitable for identifying the outcomes of actions identified by Action Coding. Pattern coding helps the researcher explores patterns of relationships between actions and their corresponding outcomes (Saldaña, 2012).

Coding analysis leads to the conceptualisations and definitions of different categories of epistemic practices and learning outcomes as well as to the revelation of the patterns of relationships between them. However, explaining the relationships, as recommended by Wynn and Williams (2012;p.799), entails "a process of abstraction that can be extended by redescribing the components parts of structure and their relationships in terms of existing theories and frameworks that provide leverage for potential explanation". Hence, an analytical framework is employed to highlight influential interactions that could explain findings.

# 4.3.2 Analytical method #2: Actor-Network Theory analytical framework

Since this research takes a socio-material perspective on learning, it chooses an analytical framework that is compatible with the perspective. Within this perspective, the Actor-Network Theory (ANT) analytical framework (Callon, 1986; Latour, 1996; Law, 2009) is especially useful as it focuses on critical moments during which influential

interactions among different types of social and materials entities, collectively called 'heterogeneous actors', take place.

ANT-analysis frames a particular case into four critical moments, collectively called the 'moments of translation', that occur in a process called 'the sociology of translation'. There are four moments: 'problematisation', 'interessement', 'enrolment', and 'mobilisation'.

- The moment of 'problematisation' involves influential attempts by different actors to frame the nature of the problem at hand according to what they know. Thus, it can highlight how engineers engaged with the knowledge that their life science counterparts used to describe life sciences problems.
- 2. The moment of 'interessement' occurs when one or more actors try to attract the interest of others through various means such as using representational artefacts to articulate their knowledge. Thus, this moment highlights the material elements from both engineering and life sciences disciplines that are possibly influential on interdisciplinary learning.
- 3. The moment of 'enrolment' occurs when actors secure the agreement of others. Those who agree will 'associate' among themselves to form a 'heterogeneous actor-network," or simply called 'actor-network'. Thus, ANT-analysis helps trace interactions and actions that lead to agreement on the appropriate actions to deal with the knowledge they encounter.
- 4. The moment of 'mobilisation' occurs when members of an actor-network mobilise the resources (also collectively considered as 'actors') of the current network in order to attract, influence, and enrol more actors towards the successful development, implementation, and diffusion of the solutions. Thus, it highlights interactions that possibly influence the accomplishment of the outcomes.

The redescription that results from an ANT-analysis brings causally relevant aspects to the foreground. However, according to principle #1, the researcher needs to abstract key actions and outcomes in terms of theoretical variables and statements of causal relationships between them. The typology method serves this need.

## 4.3.3 Analytical method #3: Typology

Social scientists often use typologies to "characterise variants of a given phenomenon in terms of conjunctions of variables." "Specified conjunctions or configurations of variables" are called "types" (George & Bennett, 2005;p.235).

Typologies consist of both independent and dependent variables. According to George and Bennett (2005), a particular 'type' is characterised, and differentiated from other 'types', based on the combination of its independent variables; the dependent variables are not considered. By treating a combination of events – such as a combination of different epistemic practices – as independent variables, the researcher then use typologies to characterise them as different 'types'.

In this research, the researcher first formulates an initial typology with an initial set of theoretical variables that correspond to the two focal events – engagements in epistemic practices and achievements of learning outcomes. The different categories of epistemic practices are treated as independent variables. Each one of them can take two possible states: either the epistemic practice is present in, or absent from, the events. The achievement of different learning outcomes is treated as different values of a dependent variable.

Such formulation of a typology specifies "the pathways through which particular types relate to specified outcomes" (George & Bennett, 2005;p.235). A pathway diagram is used to represent the specification of a pathway. It depicts the researcher's interpretation of how a combination of causal events leads to a specific outcome event. The pathway diagram is also formulated as a configuration of independent and dependent variables. The different configurations of values of the independent and dependent variables are then tabulated in a typology table that registers all the pathways in terms of the values of all the variables.

Examples of pathway diagrams, types, and the corresponding typology table are provided in Table 4.1 overleaf.

Index	Pathway diagrams	Cates episte practi prese pathv (C=C T=Tra E=Ev (0=Al 1=Pre	gories o emic ices ance ence in t vays consultat anslatio ridential bsent; esent)	f he tional; nal; );	Learning Outcomes (0=Adoption; 1=Translation; 2=Avoidance; 3=Addition)
		С	Т	E	
#1	Consultational Epistemic Practice Adoption	1	0	0	0
#2	Consultational Evidential Fistemic Practice Adoption	1	0	1	0
#3	Consultational Translational Epistemic Practice Translation	1	1	0	1
#4	Consultational Translational Evidential Evidential Epistemic Practice Translation	1	1	1	1
#5	Consultational Translational Epistemic Practice Avoidance	1	1	0	2
#6	Consultational Epistemic Practice Epistemic Practice Translational Epistemic Practice Epistemic Practice Epistemic Practice	1	1	1	2
#7	Consultational Evidential Knowledge Addition	1	0	1	3

Table 4.1: Pathway diagrams and typology table

Table 4.2 shows examples of seven different pathways (indexed #1 to #7) taken from the typological analysis of the first case study. The seven rows of the second column contain the seven pathway diagrams; the rest of the table contains the corresponding typology table.

The typology table consists of two major parts: the epistemic-practice part on the left, and the learning-outcome part on the right. The left part registers the combination of different categories of epistemic practices (independent variables), and the right part registers the learning outcomes (dependent variable).

The epistemic-practice part of the typology table is divided into a number of columns; each represents one category of epistemic practice. For example, the typology table in Table 4.2 shows three categories of epistemic practices. Each category is treated as one independent variable, which can have two values. The value for each cell in the epistemic practices columns is labelled according to the presence or absence of the particular epistemic practice. If it is present in the causal pathway, its cell is assigned a label of '1'; otherwise, it is assigned a label of '0'.

The learning-outcome part of the typology table registers the achieved learning outcomes also using labels. For example, in Table 4.2, labels '0', '1', '2', and '3' represent outcomes of Knowledge Adoption, Knowledge Translation, Knowledge Avoidance, and Knowledge Addition respectively.

Based on the contents of the epistemic-practice part of the typology table, the researcher can identify the different 'types'. In the given example, there are four 'types' that differ in the presence/absence of the three different categories of epistemic practice: Type 1= [1 0 0]; Type 2= [1 0 1]; Type 3= [1 1 0]; and Type 4= [1 1 1]. Pathway #1 is of Type 1, pathways #2 and #7 are both of Type 2, pathways #3 and #5 are both of Type 3, and pathways #4 and #6 are both of Type 4. These four types relate to specific outcomes.

The formulation of an initial typology in terms of types, pathways, and a typology table prepares the data for a further investigation of the causal relationships between the initial set of theoretical variables. However, typological analysis "alone cannot separate causal from spurious factors, or possible from unlikely or impossible combinations of variables" (George & Bennett, 2005;p.239). Nevertheless, typology formulation enables the generation of logical causal inferences. The next section describes how the comparative method generates logical causal inferences.

## 4.3.4 Analytical method #4: The Comparative Method

The comparative method is a "non-statistical comparative analysis" of a small number of instances (George & Bennett, 2005; Lijphart, 1971, 1975). It carries out three specific comparative analyses between pairs of 'types': 1) comparison between a pair of 'similar' types; 2) between a pair of 'most-similar' types; and 3) between a pair of 'least-similar' types. Table 4.2 on the next page shows the three comparative analyses, the different possible results of those analyses, the different possible indications of the results, and the different implications for further analysis.

As shown in Table 4.2, the three different comparative analyses correspond to three different characteristics of pairs of 'types': 1) 'similar' types characteristic ; 2) 'most-similar' types characteristic; 3) 'least-similar' types characteristic. A pair of 'types' is characterised as 'similar', 'most-similar', or 'least-similar' according to the following:

- 'Similar types' characteristic: A pair of types is characterised as 'similar types' when both types have the same values for all the independent variables. An example of a pair of 'similar' types consists of types from pathways #3 and #5 in Table 4.1. They both have "1", "1, and "0" values for the three categories of epistemic practices respectively.
- 2. 'Most-similar types' characteristic: A pair of types is characterised as 'mostsimilar types' when both types have the same values for all the independent variables except for one. An example of a pair of 'most-similar types' consists of the types from pathways #1=[100] and #3=[110] in Table 4.1. As indicated by the underlined values, the two pathways differ only in their values for the second independent variable.
- 3. 'Least-similar types' characteristic: A pair of types is characterised as 'leastsimilar types' when both types have the same value for only one independent

variable. An example of a pair of 'least-similar types' consists of the types from pathways #1 = [100] and #6 = [111] in Table 4.1. They have similar values for the first independent variable only (i.e. the underlined values).

Each of the three comparative analyses and the logical arguments for the possible indications and implications of their results are detailed out in subsections 4.3.4.1, 4.3.4.2, and 4.3.4.3 respectively. All the logical arguments are sourced from George and Bennett (2005).

Analyses of:	Possible results	Possible indications	Implications for subsequent analyses
Similar types – both have the same values for all the independent variables	Similar in outcomes	The independent variables they have in common are possibly causal to that similar outcome; a possible causal relationship is thus inferred	The plausibility of the causal inference needs to be evaluated by another method of analysis that can help assess its plausibility
	Differ in outcomes	There is at least one other variable that has caused the outcomes to differ; the relevant pathways have probably left out at least one causal variable	The relevant pathways need to be examined in more detail by another method of analysis that can help identify the left-out variable(s)
Most-similar types – both have the same values for all the independent variables except for one	Similar in outcomes	Either there is a presence of 'equifinality', or, the variable for which they differ could NOT possibly be the cause for the similar outcome, or, the relevant pathways have probably left out other causal variables/factors that work in conjunction with the independent variable in which they differ	The relevant pathways need to be examined in more detail so that the presence of 'equifinality' can be ascertained, or, the causal status of the variable for which they differ can be ascertained (i.e. the indication of its irrelevance is not merely a 'false negative' in that it is causal when it works in conjunction with other variables that have been left-out by the relevant pathways)
	Differ in outcomes	The one variable for which they differ could possibly be the cause of the different in outcome; a possible causal relationship is thus inferred	The plausibility of the causal inference needs to be evaluated by another method of analysis that can help assess its plausibility
Least-similar types - both have the same values for only one independent variable	Similar in outcomes	The presence of equifinality, and the one variable that they have in common could possibly be the cause for the similar outcome; a possible causal relationship is thus inferred	The plausibility of the causal inference needs to be evaluated by another method of analysis that can help assess its plausibility
	Differ in outcomes	Either the one variable that they have in common could NOT possibly be the cause for the difference in outcome, or the other variables for which they differ are possibly the causes for the difference in outcome.	The relevant pathways need to be examined in more detail so that the causal status of the variables can be ascertained (i.e. the indications are not merely 'false negative', and 'false positive').

## Table 4.2: Three comparative analysis, possible results, indications, and implications for further analysis

#### 4.3.4.1 Comparative Analysis of similar types

When the comparative method is applied to a pair of 'similar types' in an initial typology, it compares two separate events that have a similar combination of independent variables. For the initial typology in this research, it compares two separate events in which engineers have reportedly engaged in a similar combination of epistemic practices. Two different results are possible: either the events have a similar outcome, or they have a different outcome.

#### 4.3.4.1.1 Similar types with similar outcomes

The revelation that two separate events have a similar combination of epistemic practices and that both have resulted in a similar outcome is considered as an indication of a possible causal relationship. This allows the researcher to develop a logical inference that the epistemic practices have possibly caused the achievement of the learning outcome.

However, this result could only indicate a possible occurrence of a causal relationship, rather than strongly suggest, or establish, its actual occurrence in reality. This is because the comparative method does not evaluate the plausibility of a causal inference against other competing explanations; for example, against a rival explanation that contends that the causal relationship is spurious (i.e. the learning outcome is caused by another variable/factor, rather than by the epistemic practice proposed by the causal inference).

The comparative method can neither evaluate the causal priority of the independent variable (i.e. whether or not the cause itself is wholly or largely determined by another prior factor/variable), nor indicate the necessity of the independent variable for the achievement of the outcome (i.e. whether or not the outcome could also be achieved through other variables/factors). Therefore, the plausibility of the causal inference generated through comparison between similar 'types' needs to be evaluated using a different method of analysis, which is described in section 4.3.5 – The Congruence Method.

#### 4.3.4.1.2 Similar types with different outcomes

The revelation that two separate events have a similar combination of epistemic practices but have resulted in two different outcomes is considered as a deviation, rather than as a replication. The presence of such a deviation requires explanation for the achievements of different outcomes despite engagement in a similar set of epistemic practices. This result indicates that there is at least one other variable that has caused the outcomes to differ, and that the relevant pathways in the initial typology have probably left out at least one other causal variable/factor.

The implication for the subsequent analysis is that the relevant pathways need to be examined in more detail using another method of analysis called the causal process tracing method. In this way, the left-out variable(s) can be systematically traced, identified, and included in the relevant pathways. This helps refine the initial causal explanation to become a more contingent causal explanation.

For example, both of the pathways #3 and #5 in Table 4.1 have a similar combination of epistemic practices, but they have two different outcomes of Knowledge Translation and Knowledge Avoidance respectively. This indicates that there is at least one other factor/variable that has caused the difference in the outcomes. Therefore, pathways #3 and #5 need to be analysed in order to identify the left-out factor/variable.

#### 4.3.4.2 Comparative Analysis of 'most-similar types'

When the comparative method is applied to a pair of 'most-similar types' in an initial typology, it compares two separate events that have similar values for all of their independent variables except for one variable. For the initial typology in this research, it compares two separate events that have a similar combination of epistemic practices except one. An example from Table 4.1 shows that pathways #1=[100] and #2=[101] are 'most-similar types' in that they differ only in the presence/absence of the last variable, the Evidential Epistemic Practice (EEP). Two different results are possible: either the events have a similar outcome, or they have two different outcomes.

#### 4.3.4.2.1 'Most-similar' types with similar outcomes

The revelation that two separate events have two different combinations of epistemic practices but that both have nevertheless resulted in a similar outcome indicates the possibility of 'equifinality', whereby an equal outcome has been achieved through different pathways. This also indicates another possibility that the epistemic practice by which they differ may not be the cause of the similar outcome. Theoretically, this second possibility casts doubt on the causal role of that epistemic practice to the achievement of the corresponding learning outcome. An example from Table 4.2 shows that pathways #1=[100] and #2=[101] are 'most-similar types' in that they differ only in the presence/absence of the third variable, the Evidential Epistemic Practice (EEP), yet they have a similar 'Knowledge Adoption' outcome. This indicates the possible presence of 'equifinality', whereby knowledge adoption might have been achieved through separate engagements in two different sets of epistemic practices. However, such a result also casts doubt on the necessity of EEP for knowledge adoption since one can adopt knowledge without having to engage in EEP.

However, it is premature to eliminate the epistemic practice from the relevant pathway solely on the basis of such a comparative analysis due to the possibility of 'false negative' (George & Bennett, 2005;p.156), whereby a variable that appears to be non-causal turns out to be causal only when one or more other variables are present. For example, the presence of a situational factor in Pathway #2 may require engagement in EEP in order to adopt knowledge. Premature elimination will erroneously remove the EEP from Pathway #2, but will also leave out the situational factors that have caused the necessity for EEP. This will produce an inaccurate description and explanation of the phenomenon. Therefore, whenever this kind of result arises in a comparison between 'most-similar types' the researcher examines the relevant pathways in more detail using another method of the analysis (see section 4.3.6 – The Causal Process Tracing method).

#### 4.3.4.2.2 'Most-similar types' with different outcomes

The situation where two separate events with two different sets of epistemic practices that differ in only one epistemic practice and have resulted in two different outcomes indicates that the one epistemic practice for which they differ could possibly be the cause for the difference in outcome. For example, in Table 4.2, Pathways #1=[100] and #3=[110] are 'most-similar types' in that they differ only in the presence/absence of one variable – 'Translational Epistemic Practice' (TEP). Comparative analysis will reveal that they differ in their outcomes of 'Knowledge Adoption' and 'Knowledge Translation' respectively. This suggests that TEP could possibly be the cause of 'Knowledge Translation'.

Similar to earlier results that indicate a possible causal relationship, this kind of result allows the researcher to develop a causal inference, but mandates him to evaluate its plausibility using a different method of analysis, which is described in section 4.3.5 – The Congruence Method.

#### 4.3.4.3 Comparative Analysis of 'least-similar' types

When the comparative method is applied to a pair of 'least-similar types' in an initial typology, it compares two separate events that have similar values for only one of their independent variables. For the initial typology in this research, it compares two separate events that have only one epistemic practice in common. An example from Table 4.2 shows that Pathway #1=[100] and Pathway #6=[111] have similar values for the first variable only. Two different results are possible: either the events have a similar outcome, or they have two different outcomes.

#### 4.3.4.3.1 'Least-similar types' with similar outcomes

The situation where a similar outcome has resulted from two separate events that have only one common epistemic practice while the rest of their epistemic practices differ indicates the possibility of 'equifinality'. This also indicates the possibility that the one common epistemic practice could be the determining cause for the achievement of the similar outcome. Thus, a causal inference is generated and subsequently evaluated for its plausibility. The possibility that the other epistemic practices for which they differ do not play any causal role is not entertained due to the risk of 'false negative'; they may be working in conjunction with the common epistemic practice to reach a similar outcome.

#### 4.3.4.3.2 'Least-similar types' with different outcomes

The situation where two different outcomes have resulted from two separate events that have only one common epistemic practice while the rest of their epistemic practices differ indicates the possibility that the one common practice could not be the cause for the difference in outcome. However, it could also indicate the possibility that the other practices for which they differ have jointly caused the difference in outcome. An example from Table 4.2 shows that Pathway  $#1= [\underline{1}00]$  and Pathway  $#6= [\underline{1}11]$  have similar values for the first variable only (Consultational Epistemic Practice-CEP), and they have different outcomes of Knowledge Adoption and Knowledge Avoidance. The researcher might think that CEP does not play any causal role and seek to eliminate it from the pathways. The researcher might also think that the presences of the other two practices are causal to the Knowledge Avoidance outcome.

However, it is premature to eliminate the one common practice as there is a risk of a 'false negative', or to infer that the other practices are jointly causal as there is a risk of a 'false positive' in the result. As with the other results that indicate multiple possibilities, the relevant pathways are examined in more detail in the subsequent method of analysis.

The application of the comparative method at this stage of the data analysis can help generate a set of causal inferences and indicates the presence of some left-out variables/factors in specific pathways.

However, it does not help to evaluate the causal inferences against competing explanations or to identify the left-out variables/factors. Therefore, to complement the comparative method this research also employs two other methods. The first one is the congruence method of analysis, which evaluates the causal inferences against competing explanations.

## 4.3.5 Analytical method #5: The Congruence Method

The congruence method is a deductive method of testing several competing theories in order to determine which theory could best explain a case (Blatter & Blume, 2008; Odell, 2001; Rohlfing, 2012) . It involves first stating the predictions or implications that each candidate theory has for a particular case, and then corroborating them against case evidences. The theory whose predictions/implications most closely agree with the case's evidence is determined to be the best explanation (Blatter & Haverland, 2012). For this research, however, the use of the congruence method follows George and Bennett (2005) who promote its use for evaluating inferences about causal relationships between causes and their corresponding effects.

Generally, such evaluation involves treating a particular causal inference as one of the many possible explanations of how a specified outcome could have been achieved. The evaluation introduces several explanations that rival the causal inference being evaluated. The rival explanations can be generalised into three different 'general'<sup>5</sup> alternative explanations. Figure 4.2(a) on the next page depicts a 'general' causal inference that shows a possible causal relationship between an independent variable (i.e. a cause) and a dependent variable (i.e. its corresponding effect/outcome), while Figure 4.2 (b), (c), and (d) respectively depict the three 'general' alternative explanations.

Together the causal inference and its rival inferences represent an exhaustive set of four competing 'general theories' of how the value of the dependent variable could have been achieved. The congruence method examines the four competing explanations against case evidence in order to find the one that is best fit with the available evidence.

<sup>&</sup>lt;sup>5</sup> They are 'general' in the sense that no specific factor/variable is proposed. They become 'specific' if a variable/factor is specified. Thus, a competing 'general theory' can embody many 'specific theories' that embody different specified variables. In evaluating a causal inference, it basically competes against one or more 'specific theories'.



Figure 4.2: Causal inference and rival inferences

Generally, the other three rival explanations contend that the proposed causal inference is inaccurate in explaining how the dependent variable is affected. Whereas the causal inference generally proposes that the independent variable directly causes the dependent variable, as depicted in Figure 4.2 (a), the three alternative explanations respectively contend that:

- 1. The independent variable does not cause the outcome. Rather, another 'third variable' causes the outcome. In other words, the first competing explanation suspects that the causal inference is spurious, as depicted in Figure 4.2(b).
- 2. The independent variable is only an intervening variable through which a prior variable/factor acts to cause the outcome. In other words, the second competing explanation contends that the independent variable has less causal priority compared to the prior variable/factor, as depicted in Figure 4.2(c).
- 3. The independent variable is an unnecessary intervening variable because the outcome could also be achieved when the prior variable acts through another intervening variable. In other words, the third competing explanation contends that the independent variable lacks causal depth as an intervening variable, as depicted in Figure 4.2 (d).

In this research, the congruence method is used to subject the causal inferences to three consecutive evaluations labelled as C1, C2, and C3 in Figure 4.3 overleaf. The first evaluation, C1 evaluates the spuriousness of the causal inference, followed by the second evaluation, C2, which evaluates its causal priority, and the method is finally completed by the third evaluation, C3, which evaluates its causal depth. The flow of the congruence analysis is path-dependent in that its progress depends on the results of each evaluation. This path-dependent flow can be represented in the form of a Congruence Method Tree in Figure 4.3 overleaf.

Figure 4.3 shows that a causal inference is initially subjected to the first congruence analysis (C1), which evaluates its spuriousness. Its subsequent progression depends on the results of the analysis. Every analysis can result in any one of the following:

- Possible result #1: the causal inference is more congruent than its competing explanation(s)
- 2. Possible result #2: one 'specific' competing explanation is found to be more congruent than the causal inference and other available explanations
- 3. Possible result #3: the congruence method could not resolve between two or more possible explanations



Figure 4.3: Congruence Method Tree (derived from George and Bennett, 2005)

If the analysis results in either one of the first two results stated above, the researcher then moves on to the second or third analysis respectively. However, if it produces the third result (i.e. inconclusive), then the causal inference and its contending explanation(s) proceed directly to a subsequent method of analysis (see the next section 4.3.6-Causal Process Tracing) that attempts to resolve the contentions.

The following sections 4.3.5.1, 4.3.5.2, and 4.3.5.3 provide general descriptions of how the researcher performs the evaluation of spuriousness (C1), causal priority (C2), and causal depth (C3).

#### 4.3.5.1 Congruence analysis #1: Evaluating spuriousness

To evaluate the spuriousness of a causal inference, the researcher first finds candidates for specific competing explanation(s) from extant theories that offer one or more explanations for the achievement of the specified outcome. For example, if the causal inference under evaluation proposes that a particular epistemic practice causes knowledge adoption, the researcher then explores literature and theoretical perspectives that explain how knowledge adoption is achieved. The literature review on different theoretical perspectives on learning in chapter 2 can provide a selection of competing views of how professionals adopt knowledge. However, this research does not intend to seek all possible competing explanations exhaustively, nor does it seek to test the sufficiency of a particular epistemic practice in causing a particular learning outcome. Rather, it limits the explanations to the different theoretical perspectives reviewed in Chapter 2 in order to identify alternative learning practices that could have caused the achievement of the learning outcome instead of the proposed epistemic practice.

Then, the researcher specifies how the selected competing explanations would predict or explain how the engineers in the particular case adopted knowledge from different disciplines. For example, the socio-cultural perspective on learning would imply the engineers' engagement in 'legitimate peripheral participation', where a newcomer would participate as a practising member in a community of more experienced practitioners and undertake authentic tasks under their guidance, according to the Situated Learning Theory (Lave & Wenger, 1991).

Having specified the implications of each theory, the researcher then seeks for corroborating evidence. For example, the researcher would seek for evidence of actions that constitute engagement in 'legitimate peripheral participation'. If the case evidence points to the actual occurrence of such engagement, then the corresponding explanation is supported. If case evidences suggest otherwise, then it is rejected.

The researcher makes attempts to search for supporting evidence for all theoretical implications, and decide on one of the three possible results of the congruence test: spurious, not spurious, or inconclusive. He then proceeds according to the Congruence Method Tree in Figure 4.3.

#### 4.3.5.2 Congruence Analysis #2: Evaluating causal priority

To evaluate the causal priority of an independent variable, the researcher first finds candidates for the prior cause, or the antecedent, of the variable. For example, if the causal inference under evaluation proposes that Translation Epistemic Practice has caused the achievement of knowledge translation, the researcher then explores the literature for theoretical perspectives that identify possible antecedents to translational epistemic practice. For example, the framework for managing knowledge across boundaries by Carlile (2004) suggests that a knowledge barrier is the antecedent of such practice. The researcher then tries to find supporting evidences for the presence of a knowledge barrier.

The researcher searches for supporting evidence for all possible antecedents, and decides on either one of the three possible results of the congruence test. If the result found evidence to support one specific antecedent variable, the causal inference is replaced by the specific competing explanation, and the independent variable becomes an intervening variable through which the antecedent variable acts to achieve the outcome. The researcher then proceeds to evaluate the causal depth of the intervening variable.

Instead, if the results found evidence to support the causal priority of the independent variable, then the causal relationship between the independent variable and the outcome is established. The researcher then proceeds to evaluate the causal depth of the independent variable

However, if the results are inconclusive, then the causal inference needs to be subject to further analysis.

#### 4.3.5.3 Congruence Analysis #3: Evaluating causal depth

To evaluate the causal depth of an intervening variable, the researcher first finds other variables/factors that can substitute the role of the variable being assessed. The researcher can search for candidate variables from theories that offer such substitution(s). For example, if the causal inference under evaluation proposes that the existence of a knowledge barrier necessitates engagement in translational epistemic practice in order to achieve a knowledge translation outcome, the researcher can point to a view that promotes the assignment of a 'knowledge translator' role as a substitute.

The researcher seeks for evidence to corroborate the occurrence of such a substitution. If the case evidence supports it, then the necessity of the intervening variable is questionable. The researcher makes attempts to search for supporting evidence for all possible substitutions, and decides on one of the three possible results of the congruence test: having causal depth, lacks causal depth, or inconclusive. Intervening variables that have causal depth gain the 'necessary' status. Those that lack causal depth are considered unnecessary. An inconclusive result necessitates the employment of another method.

When congruence analysis results in findings that one or more explanations are congruent with the case study data, an additional assessment, called assessment of preliminary findings of congruity, is conducted (George & Bennett, 2005).

The assessment involves checking whether there are other outcomes also consistent with a particular causal relationship. In other words, the causal variables appear to cause multiple outcomes. As a result, the significance of the causal relationship in predicting any particular outcome is weakened. For example, a congruent causal relationship between a knowledge barrier, translational epistemic practice, and knowledge translation outcome lacks predictive power if the two causal variables also together produce a knowledge avoidance outcome. Another determining factor must be identified to explain how knowledge translation is achieved instead of knowledge avoidance.

The application of this method at this stage of the data analysis can help evaluate causal inferences against competing explanations and corroborate them with the case evidence. However, the congruence method of analysis can also result in inconclusive findings. Therefore, this research also employs the causal process tracing method of analysis to resolve those findings.

## 4.3.6 Analytical method #6: The Causal Process Tracing Method

The method is useful for identifying the intervening causal process that consists of sequences of cause-and-effect relationships linking a cause to its corresponding outcome (Blatter & Haverland, 2012; George & Bennett, 2005; Trampusch & Palier, 2016). By applying this method at this point of the analytical process, the researcher may be able to identify unobservable factors/variables that might be involved in the causal relationships but overlooked by the preceding analytical methods.

#### 4.3.6.1 Identifying left-out variables/factors

To identify the left-out variables, the researcher analyses the relevant pathways and identifies variables/factors that could fully explain how those pathways progress to a specific outcome. However, this research does not intend to identify all possible factors/variables exhaustively; rather, it focuses on those that could also inform students on how to be flexible in their learning in different situations. Therefore, it focuses mostly on identifying factors related to situations that are influential to the focal

events, such as how a given situation might have been perceived prior to an engagement in a certain practice or an achievement of a certain outcome.

By focusing on situational and perceptual factors, this research promotes a situational diagnosis for recognising and differentiating different situations that might demand different learning responses and outcomes. It is useful for students to able to analyse and perceive situations in order to form situational judgment on the suitable learning practices to take. For educators, it is important to recognise different situations and perceptions that have significant effects on their students' learning practices and on learning outcomes.

After inferring the possible existence of additional variables/factors, the researcher generates the relevant causal inferences and their corresponding rival inferences. Then, he evaluates the plausibility of the inferences using the Causal Process Tracing Test (CPT). The next subsection introduces the test, describes how CPT is conducted, and how it uses different evidence.

#### 4.3.6.2 Testing the plausibility of causal inferences

The effort of identifying left-out variables/factors also entails validating that the relevant causal inferences closely correspond to the actual reality. In CPT, the researcher attempts to validate two types of inferences related to a particular causal inference(Collier, 2011).

- 1. Descriptive inference, which refers to the hypothesised existence of a variable/factor
- 2. Explanatory inference, which refers to the hypothesised occurrence of the causal relationship between a cause and its effect

Van Evera (1997;pp.31-2) decomposes CPT into the following set of four different tests; each contributes in a distinct way to confirming and eliminating potential explanations (Bennett, 2010).

- 1. 'Straw-in-the-wind' test
- 2. 'Hoop' test
- 3. 'Smoking Gun' test
- 4. 'Doubly Decisive' test

Passing or failing a particular test has different implications for the inference being tested and for its rival inferences. This research mainly uses the 'Smoking Gun' test. In a 'smoking gun' test, the researcher attempts to locate and examine an additional piece of evidence in order to decide whether an inference can be confirmed. Such evidence is sufficient to confirm the plausibility of an inference. It is not a necessary evidence, however, because other pieces of evidence may also be sufficient for confirmation. In other words, the failure to locate such evidence does not mean that an inference is not plausible. Analogically, a criminal suspect who is caught holding a smoking gun right after a gunfight is confirmed as guilty (Bennett, 2010). However, a criminal suspect who is caught without a smoking gun remains a suspect because other evidences can be sufficiently used to convict him. The implications for rival hypotheses are that if the main hypothesis passed the 'smoking gun' test, then the rival hypotheses are weakened; otherwise they are somewhat strengthened (Collier, 2011).

#### 4.3.6.2.1 Descriptive 'smoking gun' test

A descriptive 'smoking gun' test requires the researcher to seek for a sufficient piece of evidence to confirm whether an inferred variable/factor corresponds to its real existence in the case being studied. It is a sufficient, but not necessary in the sense that another piece of evidence can substitute it. According to Mahoney (2012, 2015), the researcher of the case needs to find either one of the two sufficient bodies of evidences in order to pass the test.

First, s/he can seek for evidences that the case has the conditions that are sufficient for the existence of the factor/variable. If there is evidence that such conditions were present in the case, the descriptive inference is confirmed. However, they are not necessary conditions in that other conditions may also be sufficient for the existence of the factor/variable. Therefore, the absence of a piece of evidence does not eliminate the

plausibility of the existence of the variable. The logic is that, the researcher can be sure about the plausibility of the existence of a variable/factor because there are conditions that were sufficient to produce it.

Secondly, if evidence of preconditions is lacking, the researcher can also seek empirical traces left behind by the variable/factor, or so called auxiliary traces (Mahoney, 2012). The empirical traces exist if the variable/factors were necessary for producing them. Therefore, the presence of the empirical traces confirms that the necessary variable/factor exists. However, it is also likely that the traces are not available because the variable/factor was only necessary but not sufficient. Therefore, absence of such traces does not allow the researcher to eliminate the inference. It may still exist, but not sufficient to produce empirical traces.

Passing a 'smoking gun' test confirms the existence. Failing it, however, does not mean that it did not exist. Analogically, even if a suspect does not hold a smoking gun, it does not mean that we can rule out his status as a suspect.

#### 4.3.6.2.2 Explanatory 'smoking gun' test

Testing an explanatory inference depends on whether the inference involves variables/factors that are necessary or sufficient for their corresponding effects/outcomes. However, this research recognises that it is unlikely for a complex phenomenon to have one cause that can be claimed to be sufficient for producing an effect/outcome. Furthermore, it limits its focus on factors related to situations. Therefore, only explanatory 'smoking gun' tests that involve necessary variables/factors are used.

First, the researcher starts by identifying evidence of the presence of one or more intervening mechanisms that have been known, or established as necessary, for producing the outcome/effect stated in the inference. Then, he should ask if the inferred variable/factor is a necessary cause for the mechanism.
For the inference to pass the explanatory 'smoking gun' test, the variable/factor must be necessary for the intervening mechanisms as well as for the effect/outcome. If the variable/factor is not necessary for the intervening mechanisms, the causal inference fails the test since it is not plausible for the variable/factor to be a necessary cause for the outcome unless it is also necessary for the intervening mechanisms that are necessary for the outcome. However, the 'smoking gun' evidence is sufficient though not necessary. Therefore, passing confirms the causal inference, whereas failing does not eliminate it.

The CPT method completes a series of analytical methods that are employed for analysing data from one case. The findings from one case are then used to construct a preliminary theoretical framework. This framework is actually the refined and evolved version of the initial typology. The next section discusses the analytical effort of using cross-case comparison for developing contingent generalisation from a preliminary theoretical framework.

#### 4.3.7 Analytical method #7: Cross-case comparison

Cross-case comparison compares findings across a number of cases in order to achieve theoretical or analytical generalisation (Eisenhardt, 1989; Yin, 2003, 2013). Cases are selected according to the theoretical sampling method (Eisenhardt & Graebner, 2007). This section describes how findings from one case are compared with those from other studied cases in order to refine and evolve the tentative theoretical framework.

#### 4.3.7.1 Refining and evolving a theory with cross-case analysis

The organisation of the cross-case comparison for refining and evolving the tentative theoretical framework follows the building block approach offered by George and Bennett (2005). This approach is depicted in Figure 4.4 below.



Figure 4.4: Building-block approach to theory development

Figure 4.4 shows that the cross-case comparison uses a tentative theoretical framework as a basis for comparison with findings from the subsequent cases. The analysis tests whether or not the framework can adequately describe and explain the findings from the subsequent cases. Findings that can be described and explained by the tentative framework are considered as replicating the findings from the first case, thereby reinforcing the applicability of the framework.

On the other hand, findings that cannot be adequately described and explained by the tentative framework help further refine the framework with more contingent aspects of the phenomenon such as the identification of new factors/variables that cause the emergence of additional pathways that embody additional events. However, since the cases vary in the characteristics of the engineers, it is also important to test the extent to which the findings can be generalised across all the cases.

#### 4.3.7.2 Contingent Generalisation across whole sub-class

As well as being used for refining and evolving the tentative theoretical model, the subsequent cases are also used to test the extent to which the findings can be generalised across other cases. To do this testing, the researcher formulates testable propositions based on the tentative theoretical framework of the first case and uses the subsequent cases to test and update the propositions. He then tries to falsify the

prediction of the proposition using the subsequent cases. In this research, the researcher selects a least-likely case, in which the proposition is least likely to hold. If the proposition holds in the least-likely case, it can be argued that it also holds in all the other cases that are more likely than the least likely case (Flyvbjerg, 2006; Levy, 2008). If it does not, and a different epistemic practice is undertaken, then the perceptual factor that causes the divergence to the different practice can be inferred and tested for plausibility. Propositions are also tested with most-likely cases for validating them.

All the seven analytical methods need to contribute to the attainment of research quality and rigour discussed in the next section.

# 4.4 Attaining research quality and rigour

The level of quality and rigour of a research study is signified by its validity aspects, often indicated by a set of criteria, called validity criteria (Cook & Campbell, 1976; Maxwell, 2016b; Shadish *et al.*, 2002; Venkatesh *et al.*, 2013). The following subsections discuss four validity criteria and the contribution of analytical methods in attaining research quality and rigour in a qualitative critical realist research.

#### 4.4.1 Credibility

The 'credibility' criterion conventionally is concerned with ensuring that the research findings represent plausible interpretations drawn from the points of view of the informants (Graneheim & Lundman, 2004; Lincoln & Guba, 1985). Critical realist case studies, on the other hand, do not draw plausible causal explanation solely from interpreting informants' points of view. It entertains the possibility that informants have limited awareness of all the relevant causes of events and outcomes in a phenomenon. In particular, informants may have limited awareness of the underlying causal factors and unobservable causal relationships, the occurrences of which are inferred during data analysis. Hence, critical realist case studies also need to ensure credibility in drawing plausible explanations from inferences about possible causal relationships in addition to ensuring credibility in developing subjective descriptions in terms of abstract concepts

and conceptual categories (Bygstad *et al.*, 2015; Edgley *et al.*, 2016; Maxwell, 2016b; Wynn & Williams, 2012; Zachariadis *et al.*, 2013).

In this research, coding techniques ensure that the conceptual categories developed gain credibility by grounding the definition of the concepts in segments of interview data. Additionally, the comparative method ensures that only logical causal inferences are generated rather than relying solely on the subjective interpretation of the researcher. Further, the causal inferences are rigorously evaluated using the combination of two methods: the congruence method and causal process tracing tests. In this way, the research ensures credibility in drawing the most plausible causal explanation.

#### 4.4.2 Transferability

The 'transferability' criterion conventionally is concerned with ensuring that the results of a qualitative research can be generalised or transferred to other contexts or settings (Lincoln & Guba, 1985, 2000). This is usually achieved by reporting situations as 'thick' as possible so that potential knowledge users would be able to judge the extent to which situations in other contexts are similar to those in the contexts of the studied cases (Shenton, 2004). However, critical realist case studies focus more on those situations that play a significant causal role to the occurrence of focal events. This is to ensure that potential knowledge users would be able to recognise the causally relevant situations in other contexts. Hence, the adaptation of the 'transferability' criterion entails ensuring quality and rigour in the identification of situations that are causally relevant (Zachariadis *et al.*, 2013). In this research, possible causal situations are systematically: 1) coded by using the causation coding technique; 2) foregrounded by using the ANT-analytical framework; and 3) identified and evaluated by a combination of tests.

#### 4.4.3 Dependability

The 'dependability' criterion conventionally is concerned with enabling the research to be repeated and the results to be reproduced though not necessarily to gain the same results (Shenton, 2004). As well as ensuring repetition and reproducibility, critical realist studies are also concerned with enabling future research to refine or even replace the existing conceptualisation with more plausible ones. This is so that the subjective understanding of a phenomenon gains closer correspondence to the objective reality. Thus, the quality and rigour in the description of the analytical process must show clearly, how other researchers can systematically generate, evaluate, and adjudicate among, different possible explanations. This includes providing details on the supporting evidences and on how they are used to select the most plausible explanation. This would allow future research to search for evidences that have yet to be considered and for new ways in which evidences can be used for improving the subjective understanding of the phenomenon being studied (Zachariadis *et al.*, 2013).

#### 4.4.4 Confirmability

The 'confirmability' criterion conventionally is concerned with the extent to which the results could be confirmed or corroborated by others (Venkatesh *et al.*, 2013). However, critical realist studies are also concerned with the 'confirmability' of the results that conceptualise the aspects of a phenomenon that cannot be observed or were not mentioned by informants. This entails also evaluating the plausibility of the inferences of their existence, and providing empirical evidence that allows others to confirm the results of the evaluation (Zachariadis *et al.*, 2013). In this research, the detailed procedures for testing causal inferences, including possible results and their indications and implications, are provided. These provisions allow others to trace and confirm that the decisions are made based on evidence and following the given procedures.

# 4.5 Scope of applying the analytical methods

It is important to mention that this research has applied the analytical methods to study interdisciplinary projects that have been completed in the past, not those that were still ongoing during the study. Studying historical cases does not afford the researcher with the opportunity to either experience or observe the focal events (i.e. engagements in epistemic practices and achievements of learning outcomes). The researcher could not interview the informants while the events were occurring either. Consequently, this limits the scope of, and rigour in, applying the analytical methods to non-observational and non-experiential data only.

Nevertheless, by adhering to the principles of critical realist data analysis, the research could apply the analytical methods to analyse the retrospective accounts of the informants and the relevant archived materials. From a critical realist view, these retrospective accounts and archived materials are considered as part of the 'empirical traces' that were left behind by those events (Johnston & Smith, 2010).

To develop a plausible event-description that corresponds as close as possible to the actual events, this research adheres to the first principle of critical realist data analysis (Section 4.2.1: Explication of events), which prescribes the act of 'abstraction' of the 'empirical traces'. Without any engagement with the actual events, the data analysis does not adhere to the interpretivist approach, whereby the different interpretations and meanings that other research participants may have about the events are sought, analysed and consolidated for agreement.

Therefore, the descriptions of the interdisciplinary learning practices and outcomes in this research were produced solely by the researcher. The process of 'abstraction' does not include any additional feedback step for confirming any interpretation with the interviewees, or for considering any interpretive differences among a group of independent researchers.

Similarly, the explanations for the interdisciplinary learning practices and outcomes were also produced solely by the researcher without including any additional feedback step for confirming the explanation with the interviewees, or for resolving any explanatory differences among a group of independents researchers.

The application of the methods for developing the explanations adhered to the second and the third principles described in Section 4.2.2: Explication of structure and context, and Section 4.2.3: Retroduction of mechanisms, respectively. The explication of structure and context uses the ANT-theoretical framework, whereby the descriptions of the events were framed according to the 'sociology of translation' process. Again, this theoretical framing is the ANT-based re-interpretation of event-descriptions by the researcher alone without including any feedback from the other research participants.

The retroduction of the causal mechanisms uses a retroductive approach, rather than an interpretive one. Causal inferences were introduced and adjudicated through the application of the three methods: Comparative method, Congruence method, and Process-tracing method, without involving other research participants. Many of the alternative inferences were sourced from the different theoretical perspectives of learning rather than from the perspectives of the research participants, who might hold other competing, but non-learning explanations.

Thus, this research clarifies that the process and the decisions for developing the theoretical framework were made by the researcher without any additional feedback step with the interviewees or with a group of independent researchers.

# 4.6 Summary of the analytical methods

This analytical methods chapter has sought to describe how the researcher analyses case studies data using a number of analytical methods that adhere to the principles of data analysis.

Seven analytical methods have been assembled:

- Coding analysis locates and labels useful data segments to form codes and conceptual categories that help the researcher produces his initial subjective conceptualisation of a case.
- Actor-Network Theory (ANT) analytical framework. This analysis foregrounds key elements in a case and the interactions among them that help the researcher redescribes the case while highlighting critical moments and interactions that influence the engagement in different epistemic practices and the achievement of different learning outcomes.
- the analysis of the redescription of the engagement in different epistemic practices and the achievement of different learning outcomes using 'typology' as

an analytical device. This analysis characterises them as different patterns of sequences, or pathways that help the researcher delineate the different combination of epistemic practices into distinct 'types', each specifies how one or more epistemic practices lead to a specific learning outcome.

- the analysis of the distinct 'types' using the comparative method of analysis. This analysis compares the 'types', the results of which help the researcher generates logical inferences of the possible causal relationships between epistemic practices and learning outcomes.
- the analysis of the inferences of the causal relationships using the congruence method of analysis. This analysis evaluates the different causal inferences and their rival inferences, the results of which help the researcher establishes causal relationships that are congruent with case evidences.
- the analysis of the competing causal inferences using the causal process tracing method of analysis. This analysis adjudicates and resolves among competing causal inferences, the results of which help the researcher establishes causal relationships that are most plausible and incorporates them in a tentative theoretical framework for a case.
- the analysis of the tentative theoretical framework from the first case using cross-case comparisons. This analysis refines and evolves the tentative framework, the results of which help the researcher arrives at a contingent generalisation that is applicable to the chosen sub-class of interdisciplinary learning in engineering practice.

These analyses would together contribute to the attainment of research quality and rigour indicated by four validity criteria: credibility, transferability, dependability, and plausibility/confirmability. The execution of these analyses by the researcher alone has produced the results that are presented in the subsequent chapters.

# Chapter 5 Findings from heuristic case analysis

# **5.1** Chapter introduction

This chapter reports the analyses, results, and findings of the first case study, which is a heuristic case (Eckstein, 2000; Levy, 2008; Stoecker, 1991) used for developing the preliminary theoretical framework.

The chapter is organised into eight sections.

- The first section introduces the chapter and provides the background of the interdisciplinary collaboration and of the engineers who were involved in it.
- The second section reports the coding analysis that results in the identification of different categories of epistemic practice and learning outcomes and their relationships.
- The third section reports the ANT-analysis that identifies influential interactions that might explain the pattern of relationships.
- The fourth section reports the typology analysis that results in the initial typology that embodies those relationships.
- The fifth section reports the comparative analysis that generates logical causal inferences and indications of the left-out variables in the initial typology.
- The sixth section reports the congruence analysis that establishes congruent causal relationships and refines the initial typology.
- The seventh section reports the causal process tracing analysis that establishes the most plausible causal relationships and identifies left-out variables and causal relationships.
- Finally, section eight incorporates all the results into a preliminary theoretical framework.

#### 5.1.1 Case introduction

The case is an instance of interdisciplinary learning by engineers who learned life science knowledge related to a set of method and practices of cell culturing known as roller-bottle cell culturing. Genetically-modified mammalian cells are manipulated manually in roller bottles to generate bio-medicines. The learning took place in the context of a project by a leading UK biotechnology company, which in 1988 won a contract that demanded a sudden increase in its production of a therapeutic hormone.

A team of engineers and a biochemist in a Cambridge-based engineering consultancy company proposed to automate the manual method using robotics. However, the manual cell culture practices were once considered as a form of 'art-and-craft' that requires 'green-fingers' and intuition, and therefore were not initially thought to be amenable to automation (Archer & Wood, 1992; Stacey, 2012). Without any background in cell-culturing the engineers had to learn how to replicate the cell-culture method and practices in the robots. This case study studies how they practised their interdisciplinary learning during the seven months development period that ended with the successful installation of the system in January 1989<sup>6</sup>. Two engineers provided their accounts of the different aspects of their interdisciplinary learning. The next section introduces them.

#### 5.1.2 Introduction to the engineers

Two engineers who were the members of six core-development team were interviewed and their background is summarised in Table 5.1 and detailed out in the subsequent subsections.

<sup>&</sup>lt;sup>6</sup> The case is widely known for its worldwide success in transforming cell culture practices, and has since been studied as an instance of other phenomena, for example as a transition from consultancy to product business. Although the case occurred a long time ago, it was a transformative experience for the engineers, their life science counterparts, the biopharmaceutical industry, as well as for the company's business direction. This helps the informants to recall their experiences and for the researcher to locate the relevant archived documents that substantiate the accounts.

Anonymised names	Background	Prior experience relevant to the project
Informant A (Aaron)	Mechanical Engineering	Developing new robotic technologies for nuclear fuel preparation and reprocessing, and related hazardous environments.
Informant B (Baron)	Mechanical Engineering	Consultancy work for various automation projects

Table 5.1: Engineers' details

#### 5.1.2.1 Informant A

Informant A graduated in mechanical engineering in 1973. He started his career as a design engineer and became a project manager at the Atomic Energy Authority two years later. There, he oversaw the development of several new robotic technologies for nuclear fuel preparation and reprocessing, and for other hazardous environments. He was one of the pioneering member of one of the UK's first technology consulting companies, widely recognised for its role in "The Cambridge Phenomenon'. Working as the head of the Mechanical Engineering department, he initiated, together with Informant B and C, the cell-culturing automation project in 1988. Overall, he had 15 years of engineering work experience at the start of the project, but had no previous experience in life sciences-related engineering project. Thus, he can be classified as an 'experienced engineer', according to the definition of the term used in this research.

#### 5.1.2.2 Informant B

Informant B graduated from the University of Cambridge in 1973 with a degree in Engineering. He also joined Informant A as one of the pioneering members of the technology consulting company that had catalysed the Cambridge Phenomenon. He was part of the team that initiated the project in 1988. He also had 15 years of experience as an engineer, none of which is related to the life sciences. This classifies him as an 'experienced engineer'. At the time of the interview, he was the Chief Technology Officer of a life science automation company.

#### 3. Informant C

Informant C graduated in 1977 with a Bachelor of Arts in Biochemistry from the University of Oxford. She then went on to complete her an MA DPhil in Biochemistry, Biophysics and Molecular Biology in the same university. She then became a consultant in the technology consulting company and was the only one with a life science background there.

# 5.2 Coding analysis and findings

The coding analysis and results are reported in a sequence of three interrelated coding analyses as shown in Figure 5.1 below.



Figure 5.1: Sequence of three interrelated coding analyses

The coding analysis began with action coding analysis. The interview excerpts that contain actions performed on knowledge encountered are extracted from the interview transcripts. These excerpts are called 'action segments'. Then, each of these 'action segments' is assigned with an 'action code'. The 'action codes' are aggregated to form different categories of action; this produces the conceptual categories that correspond to the different 'categories of epistemic practice'.

After that, the causation coding technique combines each of the 'action segments' with the description of events that are believed to be causally related to it. This combination is denoted by the "+" sign in Figure 5.1; these are called 'causation segments'.

Then, each of the causation segments is assigned with 'causation codes', which are aggregated to form different categories of causation. This aggregation produces the conceptual categories that correspond to the two different categories of causation namely: 1) the achievement of the different categories of learning outcomes, and 2) the barriers that require further knowledge or action, or in short, the predicaments.

Finally, the pattern coding technique identifies the possible pattern of relationships between the different categories of epistemic practices and the two different categories of causation.

#### 5.2.1 Coding to categorise practices

The analysis and results of the action coding analysis are shown in Figure 5.2 below. There are a total 43 'action segments' produced. Then, the assignment of codes to those segments yielded 22 unique 'action codes', as seen in Figure 5.2, which were then categorised into three categories numbered as #1, #2, and #3 respectively.

The actions define three categories of epistemic practice:

**Consultational Epistemic Practice (CEP)** – set of activities the engineers undertook to understand life-science knowledge.

**Translational Epistemic Practice (TEP)** – set of activities of taking life-science knowledge and making it useful for engineering solutions

**Evidential Epistemic Practice (EEP)** – sets of activities that test the usefulness of the knowledge.



Figure 5.2: Analysis and results of action coding analysis

#### 5.2.2 Coding to categorise outcomes

The causation coding analysis begins by combining the 43 'action segments' produced by the action coding analysis with the description of events believed to have been caused by those actions, thereby forming the 'causation segments'. The results of the action segments may lead to a learning outcome or, alternatively may leave the engineers in a 'Predicament'. Once in a 'Predicament', the engineers have to undertake a different set of practices until they have found a way around the predicament. The results of the causation coding are shown in Figure 5.3 below. The assignment of codes to those causation segments yields 23 unique 'causation codes', which are categorised into two categories: 1) 'Achievements Codes' (AC1 to AC16 ) and 2) 'Predicaments Codes' (PC1 to PC7), as shown in Figure 5.3. The two categories of causation codes are "Achievement of Learning Outcomes" and "Predicament to Learning Outcomes".



Figure 5.3: Analysis and results of causation coding analysis

Each of the 16 Achievements Codes (AC1 to AC16) is linked to its corresponding category of epistemic practice. The interpretive formation of the causal linkages enables the researcher to represent the causation event, as shown in Figure 5.4 below.



Figure 5.4: Achievements of learning outcomes

Then, the achievements codes are used to conceptualise and define the four different categories of learning outcomes as shown by Figure 5.4.

**Knowledge Adoption** – Understand and use knowledge without altering its original meaning.

**Knowledge Translation** – Convert and use knowledge whose forms and terms are embedded in a different discipline.

**Knowledge Avoidance** – avoid pursuing knowledge because it is not believed to contribute to final solution

**Knowledge Addition** – add knowledge that is useful to the collaborators.

#### 5.2.3 Coding to identify sequences of practices

The next analysis links the seven 'predicament codes' (PC1 to PC7) to the three categories of epistemic practices that appear to have caused them. In addition, the causation segments that correspond to the seven predicament codes are analysed to find the linkage between them and the actions that the engineers take to deal with the corresponding predicaments. This subset of 17 'action codes' is differentiated from the other subset of 5 codes (i.e. codes numbered 1, 4, 7, 9, and 10) in the top-right part of Figure 5.5. It can be seen in Figure 5.5 that:

- five of the 10 'action codes' (i.e. codes numbered 1, 4, 7, 9, and 10) that are related to the CEP are follow-up actions in response to the predicaments that are encountered during the CEP.
- all of the five of the 'action codes' related to the TEP are follow-up actions to the predicaments that are related to the CEP. This indicates that TEP occurred after problematic engagements in the CEP.
- all of the seven action codes related to the EEP are follow-up actions to the predicaments that encountered in the CEP and in the TEP. This indicates that some of the engagements in EEP occurred after problematic engagements in the CEP, while others occurred after problematic engagements in the TEP.



Figure 5.5: Predicaments to learning outcomes

The above findings indicate that the engineers' activities either lead to a successful learning outcome or are unsuccessful, in which case they have to find an alternative approach. By linking the actions and the way they dealt with barriers, it is possible to determine sequences of practice leading to satisfactory outcomes.

## 5.2.4 Pattern coding analysis and findings

The third coding analysis uses pattern coding to determine the sequence of activities categorised as epistemic practices and the events that are caused by those engagements, as shown in Figure 5.6 below.



Figure 5.6: Sequential pattern of the interdisciplinary learning process

The pattern coding analysis finds that the learning sequence begins with engagements in the CEP. It then uses the results of the causation coding to represent how engagements in CEP result in achievement of a learning outcome or a predicament. The learning outcome achieved is termed as the **'consultative adoption'** outcome.

From the 'predicaments' encountered in the CEP, pattern coding uses the relevant findings from the causation coding to show the emergence of the other two categories of epistemic practice, the TEP and the EEP.

Using the same approach, pattern coding shows that successful engagement in TEP leads to learning outcomes of **'mediated translation'** and the **'mediated avoidance'**. Unsuccessful actions lead to engagement in EEP.

Successful engagements in the EEP lead to the learning outcomes, namely 'evidential adoption', 'evidential translation', 'evidential avoidance', and 'evidential addition'.

The results of the pattern coding analysis reveal the complexity of the phenomenon, whereby a specific category of learning outcomes seems to have been achieved through different sequences, each with a different sequential combination of different epistemic practices. Also, engagements in the same combination of epistemic practices lead to the achievement of different learning outcomes.

At this stage, the explanation of the case seems superficial because the results only explain that the learning outcomes are due to the successful engagements in certain epistemic practices, and that the emergence of the TEP and EEP are due to the predicaments encountered in the preceding epistemic practices. The findings could not explain why the engineers were able to undertake those epistemic practices and were successful in overcoming the predicaments, instead of abandoning their learning prematurely.

Since the conceptual framework of this research focuses on the interactions between the socio-material elements of the interdisciplinary collaboration, the influential socio-material interactions that sustain the learning process are analysed next. Therefore, the case is framed and analysed using the ANT-analytical framework.

# 5.3 Actor-Network-Theory (ANT) analysis and findings

In ANT-analysis, the ANT-analytical framework offered by Latour (1996) and Law (2009) is applied to frame the case into four critical moments, called the 'moments of translation'. There are four moments: 'problematisation', 'interessement', 'enrolment', and 'mobilisation'.

#### 5.3.1 The moment of 'problematisation'

ANT's moment of 'problematisation' refers to the part of the interaction between different 'actors' in which they attempt to render themselves indispensable to others by framing the nature of the problem at hand according to what they know. In the case studied, the 'problematisation' moment involves both the engineers and their life science counterparts problematising the same cell culture method and practices in different terms according to their own disciplinary knowledge. [see Evidence Statement 1 in Appendix 1]

As shown by the coding analysis, in some instances of 'problematisation', engineers were able to understand, appreciate, and reuse the relevant life science knowledge while retaining similar knowledge contents, meanings, and forms. Even though they did not know about the knowledge itself, they were taking perspective of the background and expertise of others and of what others might know.

However, in other instances, they view the life science's problematisation as esoteric because the knowledge descriptions tend to be in the qualitative form. Hence, they also view the knowledge from engineering perspective and recognise the need for a quantitative form of knowledge useful for engineering solution.

Viewing the same knowledge from multiple perspectives is considered as a 'mode of epistemic engagement' (Nerland & Jensen, 2012) with the knowledge described during the interdisciplinary interaction. This mode is conceptualised by this research as the '**perspectival mode of epistemic engagement'**, taking into consideration the literature on perspective structure in communication, where it has been established that in social interaction people are likely to engage in perspective-taking of the background and knowledge of others in formulating messages (Graumann & Sommer, 1988; Krauss & Fussell, 1991). It appears to influence how the engineers learnt through the different epistemic practices in at least two ways.

First, by taking the life science users' perspective, they recognised those socio-material elements with which they could consult, and interact further. Therefore, futile initial consultation with the life science users leads to selective consultations with their life science colleague whom they perceived as knowledgeable in the subject matter. This enables them to sustain learning in a consultative way and to achieve the '**consultative adoption'** outcome despite the initial predicament of not understanding the knowledge description.

Secondly, the perspectival mode of engagement seems to enable the engineers to overcome futile engagement in the CEP with their life science counterparts by engaging

in the TEP, instead of abandoning their learning. By taking the perspective of the life science counterparts who claim to be expert practitioners, the engineers were able to recognise them as sources of knowledge that they could translate into the different content and forms that are more useful for developing solutions. Thus, the perspectival mode appears to inform the correct judgement of the next action, that is the TEP, rather than to succumb to the predicaments, or to remain in consultational practice alone.

#### 5.3.2 The moment of 'interessement'

ANT's 'moment of interressement' refers to the interaction between different actors in which one or more actors try to attract the interest of others through various means. As well as being mediated by their team members, such as Informant C, who played the role of expressing the esoteric users' needs into requirement specifications, the engineers' interactions with their life science counterparts were also mediated by various representational artefacts such as drawings, simulation models, and prototypes. These mediators appear to help sustain the interests and roles of others in developing a more precise translation of qualitative and practical knowledge into the corresponding parameters and their values. The ability to represent their learning of cell culturing practice in the form of sketches, drawings and prototypes appears very influential for clarifying and confirming that they have arrived at the knowledge that enabled the solution to work satisfactorily, and thereby sustained the interest of the decision makers to allow them to proceed. [see Evidence Statements 2 & 3 in Appendix 1]

Through such mediated interactions, the engineers were able to arrive at the exact acceptable quantitative knowledge. However, their life science counterparts were also providing the engineers with the life science knowledge that underpins their agreement/disagreements that then led to other predicaments to learning. As coding analysis shows, not all the predicaments encountered in CEP were completely resolved through TEP. In some cases, there are uncertainties arising from disagreements. This invokes the need for this research to explain why the engineers were able to pursue learning despite the continuing predicaments. ANT-analysis proceeds with the 'enrolment' moment to search for the explanation of the continued sustenance of the learning process.

#### 5.3.3 The moment of 'enrolment'.

ANT's 'moment of enrolment' refers to the interaction in which one or more actors try to secure the agreement of others despite various disagreements between them. The ANT analysis highlights that the engineers sought to gain agreement of their life science counterparts that the solution being developed could better replicate the manual cell culturing. This entailed their engagement in the evidential epistemic practice.

Two modes of interaction appear to be influential in the engagement in evidential epistemic practice. One mode is conceptualised as the **justificational mode** of epistemic engagement, where the engineers appear to tolerate ambiguity in knowledge claims and saw it as opportunities to interrogate the different justification to knowledge claims and the relevant practices. They sought to rationalise what evidence could be useful for interrogating and testing different justifications in order to reach agreement. [see Evidence Statement 4 in Appendix 1]

Another mode is conceptualised as the **complemental mode** of epistemic engagement, where the engineers envisioned the improvement that could be gained from adding new knowledge to the cell culture method and practices, and thereby influencing the agreement of others. For example, [see Evidence Statement 5 in Appendix 1].

Although these modes and epistemic practices, appear to secure the agreement of the customer representatives, the engineers had to test it in the real operating environment with the real cells. Such testing requires them to 'mobilise' other 'actors' (including the actual cells) to 'agree' with the solution.

#### 5.3.4 The moment of 'mobilisation'

ANT's 'moment of mobilisation' refers to the interaction in which one or more actors try to mobilise the agreement of other stakeholders to support their 'actor-network'. ANT analysis highlights that the engineers attempted to gain the support of many 'actors' to accept the proposed solution. Firstly, they had to deal with the reality of the cells' responses, the detailed knowledge of which was unknown and appeared esoteric to acquire. Secondly, they had to deal with the social reality of human preferences and concerns about their proposed solution.

Without seeking to learn scientifically about the details of the complex realities of the behaviour and responses of the other 'actors' (i.e. cells and practitioners) whose support and agreement they seek to 'mobilise', the engineers have nevertheless appeared to seek to simply satisfy the 'actors'. They appeared to rationalise that all they needed to do was to ensure all the controls that the system provided would make the cells more stable and productive in real operations, and that the life science users are satisfied to see the workability of the solution. [See Evidence Statement 6 in Appendix 1]

#### 5.3.5 Outcome of ANT Analysis

In summary, the ANT-analysis has been valuable in turning the descriptive results of the coding analysis into more explanatory results that provide possible explanations of the learning process. It adds to the previous results in that in order to sustain interdisciplinary learning, it is not sufficient to engage only in epistemic practices but also capitalising on the socio-material elements and skills such as representing knowledge in artefacts.

It has identified three modes of epistemic engagement:

**Perspectival Mode** – where the problem is viewed through two or more different perspectives.

Justificational Mode – where engineers seek justification for ambiguous knowledge.

**Complemental Mode** – where engineers seek new knowledge to add to their understanding.

# 5.4 Typological analysis and findings

The typology analysis initiates the gradual development of a typology by incorporating the two focal events– the engagement in epistemic practices and the achievement of learning outcomes. This produces an initial typology, which is gradually refined by the subsequent analyses to also incorporate the possible influential interactions highlighted by the ANT-analysis. The following subsections provide the analyses and findings that identify the theoretical variables, specify the different 'types' of interdisciplinary learning, relate different 'types' to specific learning outcomes using pathway diagrams, and tabulate the different values of the variables.

#### 5.4.1 Theoretical Variables

The typology analysis first identifies the independent and dependent variables of the initial typology.

#### The independent variables

The independent variables correspond to the three categories of epistemic practices – CEP, TEP, and EEP. They can either be present or absent in a particular learning sequence.

#### The dependent variables

The dependent variable corresponds to the learning outcome, whose values/states can be either one of the four categories of learning outcomes: 1) Knowledge adoption; 2) Knowledge translation; 3) Knowledge avoidance; or 4) Knowledge addition.

#### 5.4.2 Different 'Types' of learning

The results of pattern coding (see 5.2.4) are used to specify four types of learning according to the different combination of epistemic practices (the independent variables).

Type #1: Learning that involves engagements in the CEP only.

Type #2: Learning that involves engagements in the CEP followed by the EEP

Type #3: Learning that involves engagements in the CEP followed by the TEP

Type #4: Learning that involves engagements in the CEP, followed by the TEP, and then the EEP.

These four 'types' of learning can result in either similar or different learning outcomes. The relationships between the different 'types' and the corresponding learning outcomes can be specified in terms of pathways to learning outcomes.

#### 5.4.3 Pathways to learning outcomes

There are seven distinct pathways that were identified in 5.2.4 linking the four 'types' and the learning outcomes as shown in the left part of Table 5.2 below. These pathways are also represented as a typology table (the last two columns of Table 5.2) that registers the values of all the variables. Such tabulation facilitates the comparative analysis between the different 'types' and pathways in order to generate a set of logical causal inferences.

Pathways index	Pathway diagrams	Categ episte and tl in the (C=C T=Tra E=Ev (0=At 1=Pre	gories o emic pra pathwa onsultat anslation idential) osent; esent)	f actices sence ays tional; nal; );	Learning Outcomes (0=Adoption; 1=Translation; 2=Avoidance; 3=Addition)
		С	Т	E	
#1	Consultational Epistemic Practice	1	0	0	0
#2	Consultational Evidential Epistemic Practice Adoption	1	0	1	0
#3	Consultational Translational Epistemic Practice Translation	1	1	0	1
#4	Consultational Translational Evidential Epistemic Practice Translation	1	1	1	1
#5	Consultational Translational Epistemic Practice Avoidance	1	1	0	2
#6	Consultational Epistemic Practice Epistemic Practice Epistemic Practice Epistemic Practice Epistemic Practice	1	1	1	2
#7	Consultational Evidential Epistemic Practice Addition	1	0	1	3

Table 5.2: Pathway diagrams and typology table

# 5.5 Comparative analysis and findings

The comparative analysis compares the four 'types' of learning identified in section 5.4.2 to produce two different kinds of outputs: 1) generation of logical causal inferences about the causal role of the individual epistemic practices, and 2) indication of some variables left out from the initial typology.

The generation of the causal inferences is provided by the following selection of three different comparisons:

- 1. Comparison between 'similar types' with similar learning outcome.
- 2. Comparison between 'most-similar types' with different learning outcomes.
- 3. Comparison between 'least-similar types' with similar learning outcome.

The indications of left-out variables, is provided by three comparisons:

- 1. Comparison between 'similar types' with different learning outcomes
- 2. Comparison between 'most-similar types' with similar learning outcomes
- 3. Comparison between 'least-similar types' with different learning outcomes

#### **5.5.1 Generation of causal inferences**

Table 5.3 shows the relevant comparative analyses, the relevant pair of pathways being compared, the logic of the comparison, and the generation of the causal inferences.

Comparative analyses	Pathways compared	Logics of the comparison (Labels used: 0=Knowledge Adoption outcome 1=Knowledge Translation outcome 2=Knowledge Avoidance outcome 3=Knowledge Addition outcome)	Causal inferences generated.
'Similar types' with similar learning outcomes	#1 vs #1	CEP is the common practice for achieving the common learning outcome = '0'	Causal inference #1: CEP is causal to Knowledge Adoption in pathway #1.
'Most-similar types' with different learning outcomes	#1 vs #3	They differ in the presence of TEP in pathway #3, where the learning outcome='1' instead of '0'	Causal inference #2: TEP is causal to Knowledge Translation in pathway #3.

Table 5.3: Comparative analyses and causal inferences

	#2 vs #4 #4 vs #7	They differ in the presence of TEP in #4, where the outcome = '1' instead of '0' or '3'	Causal inference #3: TEP is causal to Knowledge Translation in pathway #4.
	#1 vs #5	They differ in the presence of TEP in #5, where the outcome ='2' instead of '0'	Causal inference #4: TEP is causal to Knowledge Avoidance in pathway #5
	#2 vs #6 #6 vs #7	They differ in the presence of TEP in #6, where the outcome = '2' instead of '0' or '3'	Causal inference #5: TEP is causal to Knowledge Avoidance in pathway #6.
	#4 vs #5	They differ in the presence of EEP in #4, where the outcome = '1' instead of '2'	Causal inference #6: EEP is causal to Knowledge Translation in pathway #4.
	#3 vs #6	They differ in the presence of EEP in #6, where the outcome = '2' instead of '1'	Causal inference #7: EEP is causal to Knowledge Avoidance in pathway #6
	#1 vs #7	They differ in the presence of EEP in #7, where the outcome = '3' instead of '0'	Causal inference #8: EEP is causal to Knowledge Addition in pathway #7.
'Least-similar types' with similar learning outcomes	No pathways	Not Applicable	Not Applicable

As well as generating the eight causal inferences, the results also indicate the absence of logical causal inference about the possible causal role of some epistemic practices in certain pathways. For example, there is an absence of the causal inference about practices in pathway #2. As there is a risk of 'false negatives' in the results of the comparative analysis, it is premature to delete the pathway. Since the initial typology itself is still incomplete, this research considers the possibility that there are left-out variables that can possibly cause the necessity to engage in those practices.

## 5.5.2 Indication of left-out variables

There are three types of left-out variables that are indicated by the results of the comparative analysis

 Left-out variables that cause learning outcomes to differ despite engaging in a similar set of epistemic practice(s)

- 2. Left-out variables that possibly cause the necessity of engaging in an additional epistemic practice for achieving the same outcome
- 3. Left-out variables that cause divergence to a different practice that leads to the difference in learning outcomes

#### 5.5.2.1 Left-out variables causing different Learning Outcomes.

Comparative analysis between 'similar types' with different learning outcomes in Table 5.4 indicates possible left-out variables.

Table 5.4: Comparative analysis between	ʻsimilar typ	pes' with	different lear	ning
outcor	nes			

Pathways	Logics of the comparison	Indication of left-out
compared	(Labels used: U=Knowledge Adoption outcome;1=Knowledge Translation outcome; 2=Knowledge Avoidance outcome; 3=Knowledge Addition outcome)	variables
#2 vs #7	They have different outcomes ('0' vs '3') even though they both have the presence of CEP and EEP in common.	Indicates the possible presence of 'multifinality' – there is one or more other variable(s) that cause the outcomes to differ.
	versus	
	Consultational Epistemic Practice	
#3 vs #5	They have different outcomes ('1' vs '2') even though they both have the presence of CEP and TEP in common.	
	Consultational Epistemic Practice Epistemic Practice Translation	
	versus	
	Consultational Epistemic Practice	
#4 vs #6	They have different outcomes ('1' vs '2') even though they both have the presence of CEP, TEP and EEP in common	
	Consultational Translational Evidential Fistemic Practice Translation	
	versus	

	Consultational Epistemic Practice Translational Epistemic Practice Epistemic Practice Avoidance	
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# 5.5.2.2 Left-out variables possibly causing the necessity of engaging in an additional epistemic practice for achieving the same outcome

Comparative analysis between 'most-similar types' with similar learning outcomes in Table 5.5 indicates possible left-out variables.

Table 5.5: Comparative analysis between 'most-similar types' with similar learning outcomes

Pathways compared	Logics of the comparison (Labels used: 0=Knowledge Adoption outcome; 1=Knowledge Translation outcome; 2=Knowledge Avoidance outcome; 3=Knowledge Addition outcome)	Indication of left-out variables
#1 vs #2	They both have similar outcomes (=0) even though they differ in the presence of EEP in #2.  Consultational Epistemic Practice  Consultational Epistemic Practice  Consultational Epistemic Practice  Knowledge Adoption  Knowledge Adoption	Indicate two competing possibilities: 1-EEP is unnecessary for Knowledge Adoption, but beware of 'false negative', or 2-The presence of 'equifinality' - knowledge adoption outcome can be achieved via two different ways- there is one or more factor/variable(s) that cause the necessity for EEP
#3 vs #4	They both have similar outcomes (=1) even though they differ in the presence of EEP in #4.	Indicate two competing possibilities: 1-EEP is unnecessary for Knowledge Translation, but beware of 'false negative', or 2-The presence of 'equifinality'- Knowledge Translation outcome can be achieved in two different ways- there is one or more

		factor/variable(s) that cause the necessity for EEP
#5 vs #6	They both have similar outcomes (=2) even though they differ in the presence of EEP in #6.	Indicate two competing possibilities:
	Consultational Epistemic Practice Translational Epistemic Practice Avoidance VerSUS	1-EEP is unnecessary for Knowledge Avoidance; however, beware of 'false negative', or
	Consultational Epistemic Practice Translational Epistemic Practice Epistemic Practice Avoidance	2-The presence of 'equifinality'- Knowledge Avoidance outcome can be achieved in two different ways- there is one or more factor/variable(s) that cause the necessity for EEP

# 5.5.2.3 Left-out variables causing divergence to a different practice that leads to the difference in learning outcomes

Comparative analysis between 'least-similar types' with different learning outcomes in Table 5.6 indicates possible left-out variables.

Table 5.6: Comparative analysis between 'least-similar types' with different learning outcomes

Pathways compared	Logics of the comparison (Labels used: 0=Knowledge Adoption outcome; 1=Knowledge Translation outcome; 2=Knowledge Avoidance outcome; 3=Knowledge Addition outcome)	Indication of left-out variables
#1 vs #4	They only have CEP in common. Pathway #1 has only CEP, whereas Pathway #4 has CEP, TEP and EEP. Despite having common CEP, their outcomes differ ('0' vs '1') Consultational Epistemic Practice Consultational Epistemic Practice Consultational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice	Indicate two competing possibilities: 1-CEP does not play a causal role to the divergence in paths and the difference in outcomes; there may be one or more other variable(s) that actually causes the divergence, or 2-The TEP and EEP jointly cause the

#1 vs #6	They only have CEP in common. Pathway #1 has only CEP, whereas Path #6 has CEP, TEP and EEP. Despite having common CEP, their outcome differ ('0' vs '2') Consultational Epistemic Practice Consultational Epi	divergence and the difference; however, beware of 'false positives'.
#2 vs #3	They only have CEP in common. Pathway #2 has CEP and EEP, whereas Path #3 has CEP and TEP. Despite having common CEP, their outcome differ ('0' vs	Indicate two competing possibilities:
	(11) Consultational Epistemic Practice Versus Consultational Epistemic Practice Translational Epistemic Practice Translational Epistemic Practice Translational	<ul> <li>1-CEP does not play a causal role to the divergence in paths and the difference in outcomes, there may be one or more other variable(s) that cause it, or</li> <li>2-EEP may be the cause of the divergence to</li> </ul>
		adoption outcome, and TEP may be the cause of the divergence to the translation outcome; however, beware of 'false positives'.
#2 vs #5	They only have CEP in common. Pathway #2 has CEP and EEP, whereas Path #5 has CEP and TEP. Despite having common CEP, their outcome differ ('0' vs '2')	Indicate two competing possibilities:
	Consultational Epistemic Practice Consultational Epistemic Practice Consultational Epistemic Practice Consultational Epistemic Practice Knowledge Adoption Knowledge Adoption	1-CEP does not play a causal role to the divergence in paths and the difference in outcomes, there may be one or more other variable(s) that causes it, or
		2-EEP may be the cause of the adoption outcome, and TEP may be the cause of the divergence to the avoidance outcome; however, beware of 'false positives'.
#3 vs #7	They only have CEP in common. Pathway #3 has CEP and TEP, whereas Path #7 has CEP and EEP. Despite having common CEP, their outcome differ ('1' vs	Indicate two competing



Since the comparative analyses can only indicate the possible presence, but cannot locate the possible locations, of left-out variables, it is premature to give their definitive positions in the initial typology. Therefore, only the indicative positions are provided in Figure 5.7 below.



Figure 5.7: Indicative positions of the left-out variables

#### 5.5.3 Summary of comparative analysis

To summarise, the comparative analysis produces eight logical inferences about the causal relationships between individual categories of epistemic practice and specific outcomes. However, these eight causal inferences do not exhaustively encompass all the interpreted causal sequences that have been represented as the initial typology in Section 5.4. The comparative analysis also indicates that these causal sequences may be contingent upon the presence of other variables that have been left out in the initial typology. The ANT-analysis has highlighted some of the possible variables such as the different modes of epistemic engagement. Therefore, it is timely to analyse whether the inclusion of these possible variables is congruent with the case data or whether other competing variables are more congruent.

## 5.6 Congruence analysis and findings

The congruence analysis is employed to assess the eight causal inferences against other competing inferences. The assessment is carried out in three stages. In the first stage, the causal inferences are subjected to spuriousness evaluation that checks whether the outcomes could have been caused by other variables. Then, in the second stage, the causal inferences are subjected to causal priority evaluation that checks whether any of the inferred variables could have been preceded by some other variables. Finally, in the third stage, the causal inferences are subjected to causal depth evaluation that examines whether any of the inferred variables can be replaced by a different variable. All the three stages require the identification of competing variables from the literature, which precedes each evaluation.

#### 5.6.1 Spuriousness evaluation

#### 5.6.1.1 Identification of competing variables

Various literature provides a number of variables that could have caused the achievement of the different learning outcomes.

The literature on knowledge sourcing (Gray & Meister, 2006; Wang *et al.*, 2014), which is concerned with how employees learn from each other, offers three learning variables known collectively as knowledge sourcing methods (Gray & Meister, 2004). The first one is called the 'published knowledge sourcing' method, which refers to a learning practice that involves searching and accessing knowledge that has been expressed in language and separated from its originator, such as in published document (Gray & Meister, 2006). This competing variable competes with the CEP in explaining how the engineers achieve the knowledge adoption outcome; the engineers might have sourced the adopted knowledge from process and procedures documents. It is a norm for the organisations studied to publish such documents internally for references as well as externally for regulatory approval (Sweeting, 2002).

The second one is called 'dyadic knowledge sourcing', which refers to one-to-one conversation between a learner and the knowledge owner (Gray & Meister, 2006). This method is similar to the CEP.

The third one is termed "Public-Group Knowledge Sourcing", which refers to learning by attending and engaging in public knowledge arena such as in a conference (Gray & Meister, 2006). It competes with the CEP in explaining how the engineers achieve the knowledge adoption outcome; the on-going company-wide practice of sending engineers to relevant life science conferences could indicate that the public-group knowledge sourcing might be a useful practice for knowledge adoption.
Thus, two variables from the knowledge sourcing literature, 'published knowledge sourcing' and 'Public-group knowledge sourcing' are identified for spuriousness evaluation.

In addition, the situated learning theory (SLT) offers the concept of "Legitimate Peripheral Participation", that is learning through participating in a community of practitioners by performing authentic tasks under the guidance of more experienced practitioners (Lave & Wenger, 1991, 2002; Schatzki, 2017). Since the engineers were participating in the cell culture community by observing, and interacting with, the cell culture practitioners, their participation may be considered as a form of 'legitimate peripheral participation'. This can be an alternative explanation to the causal inferences.

On the other hand, the organisational knowledge and learning literature promotes the use of the 'knowledge translator' or so-called 'boundary spanner', individual or people who are knowledgeable in two or more communities (Brown & Duguid, 2001; Hargadon & Sutton, 1997; Long *et al.*, 2013). Informant C could have played such a role during the project. She might have translated life science knowledge for the engineers, instead of the latter having to engage in the TEP.

Alternatively, knowledge could have been gained from the existing translated knowledge, already embedded in existing artefacts. If knowledge existed in the form that is familiar to the engineers, then it could have been learnt and reused by them. In the project studied, existing translated knowledge was embedded in the chosen robotic platform, the Staubli RX 60 six-axis robots, in the form of a predefined sequence of movements that were considered suitable for delicate handling of cells (see Vogt, 2002).

Additionally, some of the learning outcomes could have been achieved by receiving advice and opinions from parties outside the development team. Third parties, such as external consultants who have experience in similar projects could have provided the necessary knowledge to the engineers.

The last variable considered for the spuriousness evaluation is sourced from the organisational learning literature. The literature promotes the use of 'knowledge brokers', individuals or people who create links between two or more groups and

transfer knowledge between them (Hargadon, 2002; Hargadon & Sutton, 1997; Holzmann, 2013). The possibility of having a knowledge transfer agent in the UK business environment is very high considering the existence of agencies such as the Knowledge Transfer Office.

Thus, there are seven competing variables considered in the spuriousness evaluation. Table 5.7 lists and maps them to the relevant causal inferences.

	Causal Inferences							
Competing Variables	#1: CEP is causal to Knowledge Adoption in pathway #1.	#2: TEP is causal to Knowledge Translation in pathway #3.	#3: TEP is causal to Knowledge Translation in pathway #4.	#4: TEP is causal to Knowledge Avoidance in pathway #5	#5: TEP is causal to Knowledge Avoidance in pathway #6.	#6 EEP is causal to Knowledge Translation in pathway #4.	#7: EEP is causal to Knowledge Avoidance in pathway #6	#8 EEP is causal to Knowledge Addition in pathway #7.
1-Using published knowledge sources	$\checkmark$	NA	NA	NA	NA	NA	NA	NA
2-Learning from a professional community	$\checkmark$	NA	NA	NA	NA	NA	NA	NA
3-Learning from public events-conference	V	NA	NA	NA	NA	NA	NA	NA
4-Learning from knowledge translators	NA		V	N	V	redundant	redundant	NA
5-Learning from embedded translated knowledge	NA	$\checkmark$	V	V	V	redundant	redundant	Same as variable 7-knowledge broker
6-Learning from third- party advice - consultant	Same as CEP	V	V	V	V	$\checkmark$	V	Same as variable 7
7-Learning from knowledge brokers	Same as CEP	Same as knowledge translator	Same as knowledge translator	NA	NA	Same as knowledge translator	NA	1

# Table 5.7: Mapping of competing variables to relevant causal inferences

#### Table 5.7 shows that:

- i) The 'published knowledge sourcing' variable only competes against the CEP in Causal Inference #1. It is not applicable as an alternative to the other two epistemic practices, TEP and EEP, since using 'published knowledge sourcing' to achieve the knowledge translation, knowledge avoidance and knowledge addition outcomes constitutes an engagement in the TEP and EEP respectively. Thus, the first competing variable is only applicable to causal inference #1
- ii) The 'learning from practitioner community' through legitimate peripheral participation only applies to the knowledge adoption outcome since the concept is used in the literature to describe and explain how knowledge and skills are gained.
- iii) The argument that the applicability of 'learning from public eventsconference' only competes against the CEP in Causal Inference #1 is similar to (i) above.
- iv) The 'learning from knowledge translators' mainly competes against the TEP. This corresponds to pathways #3, #4, #5 and #6. It is not applicable for the CEP in causal inference #1 since the latter involves adopting knowledge in its original untranslated form and content. For the EEP in causal inference #6 and #7, which correspond to pathways #4 and #6 respectively, the consideration of 'learning from knowledge translators' as a competing variable would be redundant since it is already considered as competing variable against the TEP, which is the practice that precede the EEP in those pathways. Additionally, if the knowledge translator adds knowledge, s/he is then considered as a 'knowledge broker'.
- v) The 'learning from embedded translated knowledge' competes mainly against the TEP.
- vi) The 'learning from a third party's advice' is applicable to all causal inference except for #1 because it would constitute the CEP.
- vii) The 'learning from knowledge brokers' is only applicable to causal inference#7 since for the other inferences it is either not applicable or redundant.

Based on the above, the spuriousness evaluation is conducted and reported in groups.

# 5.6.1.2 Group 1 - Causal relationship between CEP and Knowledge Adoption in pathway #1

The spuriousness evaluation considers the potential causal role of the three variables that represent alternative learning practices that appear to compete with the CEP (column 2 in Table 5.7).

Competing variables	Congruence analysis	Results (√=congruent; X=incongruent)
1-Published Knowledge Sourcing	The engineers might have sourced the adopted knowledge from the documented process and procedures for cell culturing. These were published internally for references as well as externally for regulatory approval. However, the inspection of the relevant documents revealed that the written descriptions contain many specialised terms, such as 'trypsinisation', as well as general terms that have specific meaning in cell culturing, such as 'sterility'. The correct understandings of the meanings of those terms were reportedly gained through consultation. [see Evidence Statements 7 & 8 in Appendix 1]	X
2-Legitimate Peripheral Participation	The engineers participated by observing, and interacting with, the cell culture practitioners. However, such participation did not involve performing the practice. Nor did it result in them gaining the ability to culture cells independently. Rather, the interaction was intended to translate only the physical movements performed by the practitioners into sequence of instructions for robotics programming. [see Evidence Statement 9 in Appendix 1]	X
3-Public-Group Knowledge Sourcing	There is no evidence that the engineers attended any relevant conference during the project. However, the on-going company-wide practice of sending engineers to relevant life science conferences could indicate that the public-group knowledge sourcing might be a useful practice for knowledge adoption. However, Informant B clarified the nature of their attendances in those conferences: " <i>we have a stand, we talk to people, we start networking.</i> " This implies the importance of the consultative part of such attendance rather than the attendance in the presentation rooms.	X

Table 5.8: Competing variables for causal inference #1 and the congruence analysis

The spuriousness evaluation indicates that the knowledge adoption outcome does not appear to be spuriously caused by the three competing variables. Therefore, causal inference #1 is congruent.

# 5.6.1.3 Group 2 - Causal relationship between TEP and Knowledge Translation in pathways #3 and #4

The spuriousness evaluation considers the potential causal role of the three variables that appear to compete with the TEP (column 3 and 4 in Table 5.7).

Table 5.9: Competing variables for causal inference #2 and #3 and the congruence
analysis

Competing variables	Congruence analysis	Results (√=congruent; X=incongruent)
1-Knowledge Translator/Boundary Spanner	Knowledge translators provided the engineers with the knowledge of the users' needs that they can express as engineering specifications. [see Evidence Statements 10 and 11 in Appendix 1] However, the knowledge translation outcome encompasses more than the translated understanding of the user needs. For example, in translating the practical knowledge of the practitioners that are implicit,	X
	engineers had to interact directly with the practitioners to elicit it: [see Evidence Statement 12 in Appendix 1] Since the knowledge provided by the knowledge translator is inadequate for gaining sufficient translated knowledge (which in pathway #4 also requires evidence), this learning from the knowledge translator is subsumed under the translational epistemic practice concept.	
2- Learning from embedded translated knowledge	Existing knowledge was embedded in the chosen robotic platform, the Staubli RX 60 six-axis robots, in the form of a predefined sequence of movements that were considered suitable for delicate handling of cells. However, engineers did not directly use those predefined sequence. As documented by Vogt (2002), the engineers and their suppliers had to "defined the sequence and speed of the robots movements" (p.50).	X
3-Third-party's advice/opinion	There was no evidence of sourcing or receiving advices from parties external to the project. Such advices seem implausible because this automation of cell culturing with robotics was unprecedented and the existing robotic sequence was not used.	X

The above results indicate that the knowledge translation outcomes in pathways #3 and #4 do not appear to be spuriously caused by the three competing variables considered. Therefore, causal inferences #2 and #3 are both congruent.

# 5.6.1.4 Group 3 - Causal relationship between TEP and Knowledge Avoidance in pathways #5 and #6

The spuriousness evaluation considers the potential causal role of the three variables that appear to compete with the TEP (column 5 and 6 in Table 5.7).

Table 5.10: Competing variables for causal inferences #4 and #5 and the	congruence
analysis	

Competing variables	Congruence evaluation	Results (√=congruent; X=incongruent)
1-Knowledge Translator/Boundary Spanner	The engineers might have managed to avoid certain knowledge suggested by the life science with the help of the knowledge translator. However, the engineers were in the better position to recognise the knowledge that would not contribute to the successful development of the solution, and avoid learning the knowledge. Hence, they were avoiding the knowledge they did not need while translating others. [see Evidence Statement 13 in Appendix 1]	X
2- Learning from embedded translated knowledge	Existing knowledge was embedded in the chosen robotic platform, the Staubli RX 60 six-axis robots, in the form of predefined sequence of movements that were considered suitable for delicate handling of cells (see Vogt, 2002). However, since the predefined sequences were not used by the engineers, they could not have caused the avoidance of other knowledge.	X
3-Third-party's advice/opinion	There was no evidence of sourcing or receiving advices from parties external to the project. Such advices seem implausible because this automation of cell culturing with robotics was unprecedented.	Х

The above results indicate that the knowledge avoidance outcomes in pathways #5 and #6 do not appear to be spuriously caused by the three competing variables considered. Therefore, causal inferences #4 and #5 are both congruent.

### 5.6.1.5 Group 4 - Causal relationship between EEP and Knowledge Translation and Knowledge Avoidance in pathway #4 and #6

As shown in Table 5.7, only one variable, 'learning from a third party' is analysed since the analysis of the other two competing variables would be redundant (see Table 5.7 column 7 and 8) and their causal roles have been ruled out in sub-section 5.6.1.3 and 5.6.1.4 respectively.

Table 5.11: Competing variable for ca	ausal inferences	#6 and #7	and the con	ngruence
	analysis			

Competing variables	Congruence evaluation	Results (√=congruent; X=incongruent)
Third-party's advice/opinion	There was no evidence of sourcing or receiving advices from parties external to the project. Such advices seem implausible because this automation of cell culturing with robotics was unprecedented and the existing robotics sequence was not used. Without any precedent, the engineers' intention to translate and avoid certain knowledge suggestion required them to prove that the automation satisfied the requirements despite using translated knowledge and avoiding some of the knowledge. They were required to show evidence that it works: [See Evidence Statements 4 and 14 in Appendix 1]	X

The results above indicate that the knowledge translation and the knowledge avoidance outcome in pathway #4 and #6 respectively do not appear to be spuriously caused by the competing variables considered. The non-learning factor of 'trust' did not appear to replace the need to show evidence that the translation and avoidance of knowledge produces a solution that satisfies the needs of the cells and the concerns of the users. Therefore, causal inferences #6 and #7 are both congruent.

# 5.6.1.6 Group 5 - Causal relationship between EEP and Knowledge Addition in pathway #7

Only one variable, 'Knowledge Broker', appears to contend with the evidential epistemic practice.

Potential spurious variables	Congruence evaluation	Results (√=congruent; X=incongruent)
Knowledge Broker	The knowledge added to the existing life science knowledge does not appear to be brokered by any individual other than the engineers themselves who had detected the opportunity, envisioned the knowledge addition, and proved that the solution worked with the added knowledge. (Evidence Statement 5 in Appendix 1]	X

Table 5.12: Competing variable for causal inference #8 and the congruence analysis

The above results indicate that the knowledge addition outcome in pathway #7 does not appear to be spuriously caused by the competing variable considered. Since acceptance and trial runs were needed, it is not plausible to suggest that the trust provided by their life science users would be sufficient either. Therefore, causal inference #8 is congruent.

In conclusion, the spuriousness evaluation of the eight causal relationships does not indicate any spuriousness in the relationships.

# 5.6.2 Causal priority evaluation

Causal priority evaluation begins by identifying possible antecedent variables whose causal role might have higher causal priority than those of the four epistemic practices before testing for congruence.

# 5.6.2.1 Possible antecedents for the Consultational Epistemic Practice in pathway #1

In identifying variables that could have higher causal priority than the CEP, the literature on knowledge adoption proposes the role of 'prior intention for adoption', defined as the combination of prior perception of the relevance and usefulness of adopting the knowledge (Feldman & Lynch, 1988; Sussman & Siegal, 2003).

Alternatively, the ANT-analysis in sub-section 5.3.1 proposes the role of the '**perspectival mode of epistemic engagement'**, taking into consideration of the literature on perspective structure in communication, where it has been established that in social interaction people are likely to engage in perspective-taking of the background and knowledge of others in formulating messages (Graumann & Sommer, 1988; Krauss & Fussell, 1991). The orientation into the perspectival mode of epistemic engagement might have enabled the engineers to recognise the expertise of others, and thereby causing their engagement in CEP.

Potential antecedents	Congruence evaluation	Results
		( $\sqrt{-congruent}$ ;
		X=incongruent)
1-Prior intention for adoption	There are indications of perception of relevance and usefulness. However, such a perception appeared to have occurred during, rather than prior to, consultation. Typically, the engineers found it difficult to understand the knowledge they encounter for the first time. For example, see Evidence Statement 15 in Appendix 1. Therefore, it is not plausible that consultation and the adoption of knowledge are both caused by the intention to adopt the knowledge prior to consultation.	X
2-Perspectival mode of epistemic engagement	Engineers appear to have taken different perspectives in the moment of 'problematisation' as shown in ANT-analysis. Without understanding the content of the knowledge encountered for the first time, the engineers relied mostly on their perception on the people who describe the knowledge to them, such as their credibility and expertise, and choose to consult them. Informant C reported on how the engineers had taken her perspective that cell culture and automation could be related: see Evidence Statement 16 in Appendix 1. In addition, Informant B recalled his perception on the expertise of Informant C: see Evidence Statement 10 in Appendix 1.	V

The above results indicate that the perspectival mode of epistemic engagement appear to have a causal priority over the other competing variables including the CEP. It enables them to consult people with the right expertise who then help them to achieve knowledge adoption. Hence, the CEP is an intervening cause through which the perspectival mode of epistemic engagement leads to knowledge adoption.

# 5.6.2.2 Possible antecedents for the Translational Epistemic Practice in Pathways #3, #4, #5 and #6

All the four relevant causal inferences (#2, #3, #4, and #5) are related to the same sequence up to and including the engagement in the TEP. Therefore, the causal priority of the TEP can be jointly evaluated.

In identifying variables that could have higher causal priority than the TEP, it is seen that the TEP is always preceded by the CEP. Therefore, it is possible that the CEP causes the TEP. Alternatively, the literature that advocates the use of knowledge translation practice suggests that the existence of barriers in communicating disciplinary concepts and assumptions often causes engagements in translational practices. Therefore, a situational perceptual variable called a communication barrier could have a higher causal priority than the TEP in causing the knowledge translation outcome.

Potential antecedents	Congruence evaluation	Results
		( $\sqrt{-congruent}$ ;
		X=incongruent)
1- Consultational Epistemic Practice	The engagement in TEP appears to be caused by prior engagement in the CEP, where the predicaments were reported to have occurred. However the engagement in CEP itself could not have been the determining cause because such an engagement had led also to divergences to other pathways (to knowledge adoption, and to EEP), rather than only to TEP in the four pathways.	X
2-Situational Perceptual variable- Communication Barrier	It appears that during CEP with the practitioners, the knowledge encountered is typically perceived as a communication barrier, a form of predicament in getting the knowledge that engineers think they need for configuring the robots.: [see Evidence Statement 16 in Appendix 1] Communication barrier appears to be the situational perception	V
	whose presence would largely cause the engineers to undertake follow-up actions that constitute the TEP. [see Evidence Statement 12] Engagement in TEP also involves avoiding some knowledge provided to them: [see Evidence Statement 13]	

Гable 5.14: Possible	variables for	TEP and the	congruence	analysis
			0	,

The above results indicate that the presence of the perception of a communication barrier appears to have causal priority over the CEP. The Knowledge Translation and Avoidance outcomes in pathways #3, #4, #5, and #6 appear to have been largely caused by the perception of a communication barrier with the TEP as an intervening variable through which the outcomes were achieved.

#### 5.6.2.3 Possible antecedents for the Evidential Epistemic Practice in Pathways #4 and #6

In identifying variables that could have higher causal priority than the EEP, it is seen that the EEP is preceded by the TEP. Therefore, it is possible that the TEP causes the EEP.

However, it is also possible that the uncertainty in the usefulness of the translated form of knowledge had caused engagement in the EEP. Therefore, the perception of the uncertain usefulness of translated knowledge could be the antecedent of the EEP.

Alternatively, the literature on engineering work and professional practice has "established that engineering work is complex, ambiguous, and full of contradictions" (Johri, 2014;p.121). More generally, professionals practices may exhibit 'discordant practices', whereby espoused values and enacted practices differ (Dall'Alba & Barnacle, 2015). Therefore, it is possible that the engineers perceived contradictory practices of their life science collaborators as a form of 'contradictory barrier', which led to seeking for evidences. Thus, a situational perceptual variable called a contradictory barrier could have a higher causal priority than the EEP.

Table 5.15: Competing variables for EEP in pathway #4 and #6, and the congruence
analysis

	( $\sqrt{-congruent}$ ;
	X=incongruent)
EP appears to be caused by prior engagement in TEP in bathway #4 and #6. However, it could not have been the letermining cause because engagement in TEP also led to the achievements of knowledge translation or knowledge avoidance butcome without having to engage in the EEP.	X
t appears that in instances where the perception of usefulness of the translated is uncertain, the engineers proceed with the evidential epistemic practice to ascertain its use. The uncertainty urise because the results of using translated knowledge and evoidance of some have yet to be known in a real operation, and hereby postponing their acceptance until evidence is shown. see Evidence Statement 3 in Appendix 1] The situation was perceived as uncertain for both parties since in leveloping the solution, the engineers had translated the	V
	P appears to be caused by prior engagement in TEP in thway #4 and #6. However, it could not have been the termining cause because engagement in TEP also led to the the termining cause because engagement in TEP also led to the the termining cause because engagement in TEP also led to the the termining cause because engagement in TEP also led to the the termining cause because engagement in TEP also led to the the translated is uncertain or knowledge avoidance the translated is uncertain, the engineers proceed with the ridential epistemic practice to ascertain its use. The uncertainty ise because the results of using translated knowledge and roidance of some have yet to be known in a real operation, and ereby postponing their acceptance until evidence is shown. the situation was perceived as uncertain for both parties since in eveloping the solution, the engineers had translated the tailitative description of the process into different forms of

	knowledge (sketches, parameters, and quantitative values) that configure the robots. They had also avoided the exact speed of movement practised by the practitioners, but had to test the impact of the fast movement to the cells. [see Evidence Statement 20 in Appendix 1]	
3-Perception of knowledge encountered as contradictory barrier	It is also possible that perceiving the knowledge claim as contradiction can also lead to knowledge avoidance. This is related to the knowledge about the effect of shear stress and the need to replicate 'green fingers' in the robots. The knowledge was perceived as discordant by the engineers because the actual practices appear contradictory to the knowledge suggestion.[see Evidence Statement 18 in Appendix 1] However, the interview data suggests that the perception of a contradictory barrier directly leads to EEP,[see Evidence Statement 4 in Appendix 1], without engaging in the TEP as in pathway #4 and #6. This seems to be a different pathway to EEP as represented earlier in pathway #2.	X

The results above indicate that the presence of the "perception of uncertain usefulness" variable appears to have causal priority over the other competing variables. Knowledge Translation and Knowledge Avoidance outcomes in pathways #4 and #6 are respectively caused by the prior perception of uncertain knowledge usefulness with the engagement in EEP as the intervening practice through which the outcomes were achieved.

Additionally, the test found the causal priority role of the perception of a contradictory barrier during CEP, which leads to EEP as earlier conceptualised as pathway #2. This is related to the knowledge about the effect of shear stress and the importance of having 'green fingers' where there are differences in opinions.

### 5.6.2.4 Possible antecedents for the Evidential Epistemic Practice in pathway #7

In identifying variables that could have higher causal priority than the EEP in pathway #7, it is seen that the EEP is preceded by the CEP. Therefore, it is possible that the CEP causes the EEP. Alternatively, it is also possible that the engagement in the EEP is

preceded by a barrier to contributing engineering knowledge to the life science discipline. The causal priority of this 'contributory barrier' is investigated below.

Potential prior variables	Congruence evaluation	Results
		( $\sqrt{-congruent}$ ;
		X=incongruent)
1- Consultational Epistemic Practice	EEP appears to be caused by prior engagement in CEP, causing the engagement in the EEP in pathway #7. However, it is not the determining factor because the engagement in CEP led also to divergence in other pathways.	X
2-Contributory Barrier	Contributory barrier appears to be the situation that wholly caused the follow up actions that constitute EEP. The difficulty in contributing knowledge to the life science domain without providing the relevant evidence causes the subsequent engagement in EEP to show evidence of performance optimisation. [see Evidence Statement 5 in Appendix 1]	V

Table 5.16: Competing variables for EEP in pathway #7, and the congruence analysis

The above results indicate that the perception of a contributory barrier appears to have causal priority over the other competing variable.

# 5.6.2.5 Conclusion of causal priority evaluation

The results show that all the epistemic practices in the pathways are largely caused by the corresponding prior variables:

- i. Engagement in CEP is caused by prior orientation in the perspectival mode of epistemic engagement
- ii. Engagement in TEP is caused by prior perception of a communication barrier
- iii. Engagement in EEP following TEP is caused by prior perception of uncertain usefulness in the translated knowledge
- iv. Engagement in EEP following a CEP is caused by prior perception of a contributory barrier
- v. Additionally, the prior cause of EEP in pathway #2 was found (i.e. the contradictory barrier), thereby supporting the applicability pathway #2

and the contingent role of engagement in EEP for achieving knowledge adoption.

# 5.6.3 Causal depth evaluation

Causal depth evaluation assesses whether or not the different categories of epistemic practice are necessary intervening variables through which the corresponding learning outcomes could be achieved. The researcher considered that all the seven variables that were involved in the spuriousness evaluation should be evaluated for their ability to substitute for the roles of the epistemic practices.

### 5.6.3.1 Causal relationship between CEP and Knowledge Adoption in pathway #1

There are three variables that contend with the intervening causal role of the CPE in pathway #1.

Potential alternative variables	Causal depth evaluation	Results (√=substitutable; X=not substitutable)
1-Published Knowledge Sourcing	It has been noted in the spuriousness evaluation that the relevant published knowledge sources contain many specialised terms, such as 'trypsinisation', as well as general terms that have specific meaning in cell culturing, such as 'sterility'. Relying on published knowledge sourcing without consulting the more knowledgeable others would increase the risk of misunderstanding on how to reuse them. Thus, this method of knowledge sourcing does not appear to be a better or equivalent substitute to engagement in consultative epistemic practice. This is especially the case when the engineers recognised, through the perspectival mode of epistemic engagement, that their life science counterparts have the expertise and credibility.	X
2-Legitimate Peripheral Participation	It has been noted in the spuriousness evaluation that the engineers participated in, but avoided performing or adopting the cell culture practice. Such practice requires long specialist training to develop skills in manipulating cells, yet there is no guarantee of consistency in manual handling, which was why the company opted for automation. Therefore, it is unlikely that the legitimate peripheral participation can be a better or equivalent substitute to consultational epistemic practice.	X

Table 5.17: Competing variables for CEP in pathway #1, and the congruence analysis

3-Public-Group Knowledge Sourcing	As clarified in the spuriousness evaluation, the engineers' attendance in group knowledge arena, such as in conferences, is actually consultative in nature. This seems to indicate that their presence in a conference targeted for life science audience may not substitute their learning through consultation. These kind of conferences involve life science speakers presenting their knowledge using disciplinary jargons. As the literature on knowledge sourcing has suggested, learning in public venue "discourage repeated interactions between source and recipient" as "participants are intolerant of in-depth discussion" which "takes up time and attention" (Gray & Meister, 2006;p.147). Therefore, it is not a better or equivalent substitute to engagement in the CEP.	X

The above results indicate that engagement in CEP is necessary for achieving knowledge adoption through pathway #1 since the three competing variables do not appear to be equivalent or better substitutes for CEP.

# 5.6.3.2 Causal relationship between TEP and Knowledge Translation in pathways #3 and #4

There are three variables that contend with the intervening causal role of TEP in pathways #3 and #4. However, the potential substitutive role of third party's advice has been ruled out.

Potential alternative variables	Congruence evaluation	Results (√=congruent; X=incongruent)
1- Knowledge Translator/Boundary Spanner	A knowledge translator was helpful in overcoming the perception of communication barrier when it comes to dealing with knowledge about user's needs. However, as considered in the spuriousness evaluation, the knowledge translation outcome requires more than relying on knowledge translators' understandings of the users' need. Instead, it requires engineers to interact with the practitioners for translating knowledge. This is evident by the on-going practice of taking engineers to meeting with the customers. Evidence Statement 13	X
2-Existing knowledge	Existing knowledge embedded in the chosen robotic platform, the Staubli RX 60 six-axis robots, in the form of predefined sequence of movements that was considered suitable for delicate handling of cells, was not helpful in situation that is perceived as communication barrier. Engineers needed to <i>"defined the sequence and speed of the robots movements"</i> (Vogt, 2002;p.50). Protocols and process parameters that drive the robotic arm were also derived from practice rather than reusing the embedded programmes. Hence, existing knowledge is not a substitute to engagement in translational epistemic practice.	X

Table 5.18: Competing variables for TEP in pathway #3 and #4, and the congruence analysis

The above results indicate that the engagement in TEP is necessary for achieving the knowledge translation outcome in pathway #3 and #4 since the two competing variables do not appear to be equivalent or better substitutes for TEP.

# 5.6.3.3 Causal relationship between TEP and Knowledge Avoidance in pathways #5 and #6

There are two variables that contend with the intervening causal role of translational epistemic practice through pathways #5 and #6.

Table 5.19: Competing variables for	TEP in pathway	#5 and #6,	and the co	ongruence
	analysis			

Potential alternative variables	Congruence evaluation	Results (√=congruent; X=incongruent)
1-Knowledge Translator/Boundary Spanner	With their knowledge of users' needs and biologically acceptable options, knowledge translators can play an important role to avoid knowledge description that is not relevant. However, as shown in the spuriousness evaluation, this does not substitute the need for the engineers to involve in the interaction because typically the engineers have more knowledge about what is not relevant or practical to be included in the solutions that they proposed.	X
2-Existing knowledge	Even though the robotic platform has an embedded knowledge about sequence of movements that are considered suitable for cell culturing, and thereby informing what is relevant and practical for the robot to do, these knowledge were themselves configured by, rather than dictate, the development, as reported by Vogt (2002). Engineers would still need to interact with their life science counterparts to gain the parameters and values to configure the robot. Therefore, the extent to which existing solution can help avoid knowledge is limited and do not substitute the role of engineers in engaging in translational epistemic practice.	X

The above results indicate that engagement in TEP is necessary for the knowledge avoidance outcome in pathway #5 and #6 since the two competing variables do not appear to be equivalent or better substitutes for TEP.

#### 5.6.3.4 Causal relationship between EEP and Knowledge Translation and Knowledge Avoidance in pathway #4 and #6 respectively

Both knowledge translation and avoidance outcomes can be achieved without engaging in EEP, as represented by pathway #3 and #5 respectively. Therefore, it raises the question of was it necessary to engage in EEP following the engagement in TEP. There are two variables that could possibly substitute for evidential epistemic practice when the usefulness of the translated knowledge or knowledge avoidance is uncertain.

Table 5.20: Competing variables for	EEP in pathway	<sup>•</sup> #4 and #6	, and the	congruence
	analysis			

Potential alternative variables	Congruence evaluation	Results (√=congruent; X=incongruent)
1- Knowledge Translator/Boundary Spanner	Knowledge translator plays an inadequate causal role to the achievement of either knowledge translation or knowledge avoidance outcome. In fact, when perceived uncertainty arises, the interaction with knowledge translator did not remove the necessity to provide evidence of the workability of the solution during the acceptance test with real cells.	X
2-Third-party's advice/opinion	Opinion from an outsider was hard to get because the project was unprecedented. Even if there were one, it would not substitute for the need to show evidence as tests are mandatory for conformance to regulatory requirements.	X

The above results indicate that engagement in EEP is necessary for the knowledge translation and knowledge avoidance outcomes in pathways #4 and #6 (when ambiguity and uncertainty arise) respectively since the two competing variables do not appear to remove the necessity to engage in the EEP.

### 5.6.3.5 Causal relationship between EEP and Knowledge Addition in pathway #7

One variable contends with the evidential epistemic practice. It is analysed in Table 5.21.

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Potential alternative variables	Congruence evaluation	Results (√=congruent; X=incongruent)
Knowledge Broker	The knowledge added to the existing life science knowledge does not appear to be brokered by any individual other than the engineers who demonstrate that knowledge addition works. However, if available, they can substitute the engineers brokering role. Nevertheless, as in most development projects, the necessity of showing evidence that knowledge combination results in solutions that work still rest on the engineers.	X

The above results indicate that engagement in EEP is necessary for the knowledge addition outcome in pathway #7 because the competing variable does not appear to remove the necessity for EEP when knowledge description is perceived as a contributory barrier.

# 5.6.3.6 Conclusion of causal depth evaluation

The causal depth evaluation establishes the likelihood that all three different categories of epistemic practices are necessary intervening variables for achieving the corresponding learning outcomes in all the relevant pathways.

Overall, it appears that the congruence analysis results in a congruent description and explanation of the interdisciplinary learning; all the pathways are furnished with the relevant variables. However, this congruence needs to be assessed in order to indicate any incompleteness in explanation.

# 5.6.4 Assessment of the congruent findings

The assessment of the congruent findings is tabulated in Table 5.22 below.

	Congruent causal relationships	Assessment
1	CEP is causal to Knowledge Adoption (from spuriousness evaluation in subsection	Engagement in CEP also led to effects other than the achievement of knowledge adoption outcome. The divergence to other epistemic practices is the other effect. Therefore, the role CEP as the intervening variable that

Table 5.22: Assessment of all the congruent causal relationships.

	5.6.1.2). However, it is only an intervening variable (from causal priority evaluation in subsection 5.6.2.1), though a necessary one (from causal depth evaluation in subsection 5.6.3.1)	determines knowledge adoption is weakened.
2	TEP is causal to Knowledge Translation and Knowledge Avoidance (from spuriousness evaluation in subsection 5.6.1.3 & 4). However, it is only an intervening variable (from causal priority evaluation in subsection 5.6.2.2), though a necessary one (from causal depth evaluation in subsection 5.6.3.2 & 3)	Since engagement in TEP leads to more than one outcomes, its role in determining a specific outcome is weakened. Additionally, it was found in the causal priority evaluation in subsection 5.6.2.3 that it was the perception of the uncertain usefulness, or relevance, of the translated knowledge that are more likely to lead to the subsequent engagement in EEP following and engagement in TEP. Therefore, the 'perceived relevance' is the variable that determines either the achievement of Knowledge Translation or Knowledge Avoidance, or the change in practice to EEP.
3	EEP is causal to Knowledge Translation, Avoidance and Addition (from spuriousness evaluation in subsections 5.6.1.5 & 6)	Pathways that pass through EEP are pathway #2, #4, #6, and# 7 with the outcomes of Knowledge Adoption through Evidential Adoption, Knowledge Translation through Evidential Translation, Knowledge Avoidance through Evidential Avoidance, and Knowledge Addition through Evidential Addition respectively. However, engagement in EEP may fail to achieve the outcomes when the evidence is unacceptable. Moreover, it relates to more than one outcome. Therefore, EEP is not the determining cause for those outcomes.
4	Perspectival Mode of Epistemic Engagement is causal to CEP (from causal priority evaluation in subsection 5.6.2.1)	Since the orientation into the perspectival mode of epistemic engagement enables the engineers to recognise the expertise of others, it is more likely to cause engagement in CEP rather than in other learning approaches. However, it is unlikely that the perspectival mode of epistemic engagement alone is sufficient. Therefore, it is a necessary, though insufficient cause for CEP.
5	Communication Barrier is causal to TEP (from causal priority evaluation in subsection 5.6.2.2)	Communication barriers can also lead to aborting the learning, instead of engaging in TEP. Therefore, the role of communication barriers as the determining cause of TEP is weakened.
6	Contradictory Barrier is causal to EEP (from causal priority evaluation in section 5.6.2.3)	Contradictory barriers can also lead to aborting the learning, instead of engaging in EEP. Therefore, the role of contradictory barrier as the determining cause of EEP is weakened.
7	Perception on the uncertain usefulness/relevance is causal to EEP (from causal priority evaluation in subsection 5.6.2.3)	Testing and providing evidence is the way to ascertain the usefulness/relevance of the translated knowledge. However, it is unlikely that such a perception alone is sufficient. Therefore, it is a necessary, though insufficient cause for the EEP.
8	Contributory Barrier is causal to EEP(from causal priority evaluation in subsection 5.6.2.4)	Contributory barriers can also lead to aborting the learning, instead of engaging in EEP. Therefore, the role of contributory barrier as the determining cause of EEP is weakened.

Based on the above assessment, it can be concluded that the congruence analysis refines the initial typology. However, there are five congruent relationships (numbered 1, 3, 5, 6, and 8 in Table 5.22) in which the corresponding causal variables do not determine the outcomes and the determining variables have yet to be identified. This requires the identification of the left-out variables using the causal process tracing analysis.

# 5.7 Causal process tracing analysis and findings

Causal process tracing analysis identifies variables left out from the refined typology, tests the plausibility of the inferences about their existences and about the occurrences of the relevant causal relationships. The pathways of the refined typology are traced to locate the possible position of the left-out variables, which are represented by the five dotted-ellipses in Figure 5.8 below.



Figure 5.8: Possible locations of the left-out variables in the refined typology

# 5.7.1 Tracing variable #1

The pathways diagram in Figure 5.8 indicates that engagement in CEP is likely to subsequently diverge into four separate paths. In the previous analysis, three of these

divergences have been described and explained by the identification of the three different situational perceptual variables:

- 1) a communication barrier;
- 2) a contradictory barrier; and
- 3) a contributory barrier.

Therefore, the one left-out variable whose presence is likely to lead to the achievement of the knowledge adoption outcome is also identified as a type of situational perceptual variable, conceptualised as the 'perception of the situation as analogous'.

# 5.7.1.1 Identifying the variable

The identification of the 'analogous perception' variable is also informed by the literature on analogy and constraint transfer, which theorises the use of analogy to acquire and retain new learning materials by making the connection between new knowledge to prior knowledge (Aubusson *et al.*, 2006; Gentner & Colhoun, 2010; Gentner & Holyoak, 1997; Gentner *et al.*, 2003; Holyoak, 2012; Stepich & Newby, 1988). This identification leads to the inferences that:

- the engineers had perceived the knowledge they encountered as analogous to their prior knowledge or experience
- 2. the analogous perception had contributed to the achievement of a knowledge adoption outcome

### 5.7.1.2 Testing descriptive inference

In testing the plausibility that the analogous perception occurred, the researcher has located auxiliary traces left behind by such an occurrence. These traces emerged during the interviews and are supported by the relevant archived data.

- 1. In the interview data: Informant C recalled that she convinced the engineers to perceive the knowledge related to the cell culturing practice as similar to their prior knowledge and experience in electronics assembly in terms of its repetitive nature that is amenable to automation and of the meaning of sterility as particle-free operation. [see Evidence Statement 17 in Appendix 1: Informant C]
- 2. In the archived data: The connection between the repetitive nature of the cell culturing method and automation has also been reported elsewhere. For example, Vogt (2002;p.49) stated that "process applied in pharmaceutical laboratories...are essentially repetitive in nature and therefore very suitable for automation". Similarly, Chapman (2003;p.663) stated, "Cell culture...is traditionally a manual process that demands hours of repetitive, painstaking work to ensure absolute sterility under exacting conditions." Since these publications were published independently from, and prior to, this research, the perception reported during the interview is unlikely to result from the 'impression management' of the informants.

Since the presence of the analogous perception is necessary for the above auxiliary traces to have existed, the traces could be counted as 'smoking gun' evidence according to the CPT procedure (Subsection 4.3.6.2.1). Therefore, the plausibility of the presence of the analogous perception is confirmed on the basis of the 'smoking gun' test.

# 5.7.1.3 Testing the explanatory inference

In testing the explanatory inference that the presence of analogous perception is likely to cause the adoption of knowledge, this research has located the mechanism of *'relating'* by which new knowledge is associated with prior knowledge, thereby enabling the learner to acquire, retain, and retrieve the newly acquired knowledge (Ertmer & Newby, 2013; Stepich & Newby, 1988). Evidence that the *'relating'* mechanism operated in the case were found in the interview and the archived data.

 In the interview data: Informant A recalled how he was analogically relating the practical knowledge of cell culturing to a process knowledge that was familiar to him: [see Evidence Statement 18 in Appendix 1]. In this way, the team realised that the repetitive aspects of the knowledge, rather than the intuitive 'art-andcraft' practice of cell culturing, seemed to be the more useful knowledge to acquire. Since they had already learnt other similarly repetitive procedural knowledge, they knew how to organise the knowledge into a form of process steps that matched with their mental model of the repetitive process.

2. In the archived data: A journal paper reported how the process was related to knowledge and experience in automation and control engineering: "The manual process was thought to be unpredictable due to the uncontrolled biological variables involved. Experience with an automated method suggests that if all the variables are very tightly controlled then predictable cell stripping always occurs" (Archer & Wood, 1992;p.403). A relevant paper on pharmaceutical processes draws a similar parallel and remarked "Pharmaceutical processes have distinct parallels with manufacturing" (Piggin, 2002;p.9).

Since the presence of the analogous perception is necessary for the *'relating'* mechanism to operate, and the *'relating'* mechanism in analogical learning is necessary for the knowledge adoption outcome, the above evidence could be treated as 'smoking gun' evidence. Thus, the test confirms the plausibility that the analogous perception is likely to have caused the knowledge adoption outcome in pathway #1.

# 5.7.2 Tracing variable #2

The pathways diagram in Figure 5.8 indicates that there is a left-out variable, which enables the engineers to overcome the perceived communication barrier. The identification of the left-out variable makes use of the results of ANT analysis in the moment of 'problematisation'. There, the presence of the perspectival mode of epistemic engagement, in which the engineers were taking different perspectives, is possibly influential to the subsequent engagement in the TEP. Therefore, the perspectival mode is the suspected missing variable.

#### 5.7.2.1 Identifying the variable

The identification of the variable is also informed by the literature on communities of knowing (Boland & Tenkasi, 1995) that emphasises the importance of perspective taking and perspective making. Perspective taking involves taking the perspective of others into account due to the recognition of their specialisations(A. Grant & Berry, 2011), whereas perspective making involves developing and strengthening one's own knowledge domain and practices (Boland & Tenkasi, 1995; Markauskaite & Goodyear, 2017). It is therefore inferred that, following the perception of the situation in interdisciplinary interaction as a communication barrier:

- 1. the engineers had oriented their epistemic engagement in the perspectival mode, and
- 2. the perspectival mode of epistemic engagement had contributed to their engagement in the TEP

#### 5.7.2.2 Testing the descriptive inference

In testing the plausibility that the perspectival mode occurred, the researcher has located auxiliary traces left behind by such an occurrence. These traces emerged during the interviews and are supported by the relevant archived data.

- During the interview: The engineers explicitly recalled how they reflexively took an engineering perspective in order to gain precision in the process description and its parameters. An exemplar situation was recalled. (see Evidence Statement 12 in Appendix 1: Informant B]. Nevertheless, at the same time the engineers were taking the users' perspective to elicit important knowledge related to their vision of an automated operation. [see Evidence Statement 19 in Appendix 1: Informant B]
- 2. In the archived data: Both Vogt (2002) and Kempner and Felder (2002;p.3) documented that existence of the relevant process parameters in the commissioned system, for example, the various "*user-defined parameters such as robot movements, process volumes, temperatures, and trypsinization timing.*" Since

the cell culture automation had no precedent, the engineers could not have copied those precise parameters from elsewhere.

Since the perspectival mode of epistemic engagement is necessary for the above auxiliary traces to have existed, the traces could be counted as 'smoking gun'. Therefore, the existence of the perspectival mode of epistemic engagement is confirmed on the basis of 'smoking gun' test.

### 5.7.2.3 Testing the explanatory inference

In testing the causal inference that the presence of the perspectival mode of epistemic engagement had caused the engagement in TEP, this research again draws on the literature on communities of knowing. The literature emphasises the importance of the cognitive mechanism, called 'representing', by which a member of one community creates a visible representation of one's understanding of knowledge within a perspective (Boland & Tenkasi, 1995; Prain & Tytler, 2012; Van den Broek, 2010).

Evidence that the 'representing' mechanism operated in the case was found in the interview and the archived data.

- 1. In the interview data: Informant A recalled how the team represented the qualitative description of the manual cell culture method in quantitative, visual, and physical forms that enabled them to subsequently engage in translating the 'art-and-craft' description of the practical knowledge into translated knowledge that drives the robot to successful automation: see Evidence Statement 20 in Appendix 1.
- 2. In the archived data: A journal paper captured the engineers' representation of the system (Archer & Wood, 1992)

Since the perspectival mode of epistemic engagement is necessary for the 'representing' mechanism to operate, and the operation of the 'representing' mechanism is necessary for the engineers' engagement in the TEP, the above evidence could be treated as 'smoking gun' evidence. Thus, the test confirms the plausibility that the perspectival mode of epistemic engagement is likely to have caused the engagement in the translational epistemic practice.

# 5.7.3 Tracing variable #3

The pathways diagram in Figure 5.8 indicates that there is a left-out variable, which enables the engineers to overcome the perceived contradictory barrier. The identification of the left-out variable makes use of the results of the ANT analysis on the moment of 'enrolment'. There, the presence of the justificational mode of epistemic engagement, in which the engineers were seeking for justifications in response to the knowledge provided to them, is seen as influential to their subsequent engagement in the EEP. Therefore, the justificational mode is the suspected missing variable.

#### 5.7.3.1 Identifying the variable

The identification of the missing variable is also informed by the literature on engineering work and professional practice, which has "established that engineering work is complex, ambiguous, and full of contradictions" (Johri, 2014;p.121), and professionals practices may exhibit 'discordant practices', whereby espoused values and enacted practice differ (Dall'Alba & Barnacle, 2015). The literature emphasises the necessity of developing awareness and tolerance for dealing with complexity, ambiguity, and contradictions in professional practice (Baer, 1986; Budner, 1962; Furnham & Ribchester, 1995). Tolerating ambiguity involves reacting favourably to situations perceived as unfamiliar, complex, dynamically uncertain or subject to multiple conflicting interpretation, perceiving them instead as opportunities for interrogating practice and for developing alternative, and more fruitful, practice. Professionals need to tolerate ambiguity and contradictions by inquiring into the knowledge of the justifications and rationales that underpinned those ambiguities and contradictions. It is therefore inferred that, following the perception of the situations in interdisciplinary interaction as contradictory barriers:

1. the engineers had oriented their epistemic engagement in the justificational mode to inquire into the knowledge that underpins the existing practices to be interrogated, and

 the justificational mode of epistemic engagement had contributed to their engagement in the EEP to gather the evidence related to the contradictory knowledge claims

### 5.7.3.2 Testing the descriptive inference

In testing the plausibility that orientation into the justificational mode occurred, the researcher has located auxiliary traces left behind by such an occurrence. These traces emerged during the interviews and are supported by the relevant archived data.

- During the interview: The engineers explicitly recalled how they were tolerantly inquiring into and interrogating justifications of the knowledge claims about the impact of mechanical forces on cells behaviours, the knowledge of which seemed contradictory to the engineers' observation of the actual practices. See Evidence Statement 4 in Appendix 1: Informant A recalled how the justifications and rationales were inquired into by the engineers: See also Evidence Statement 21: Informant C also recalled being in the justificational mode with the team in order to inquire into the practical knowledge that underpins practice and to interrogate the existing practices: see Evidence Statement 22.
- 2. In archived data: Public presentations made by the informants also contain these justifications and rationale for maintaining the manual cell manipulations over automated operation, but at the expense of contradicting the objective of reducing contamination and variability in the process. The automation-based solution is considered as *"challenges accepted dogma"* (Drake, 2011;p.7). Similarly, a paper published the statement that *" The prevailing view was that Biology could not be easily reduced to process...those views had to be challenged and ways had to be found to reduce at least some parts of the work to process...to make the more repetitive tasks amenable to other methods"* (Archer & Wood, 1992;p.403).

Since the occurrence of the justificational mode of epistemic engagement is necessary for the above traces of to have existed, the traces could be counted as 'smoking gun' evidence. Therefore, the presence of the justificational mode is confirmed on the basis of 'smoking gun' test.

#### 5.7.3.3 Testing the explanatory inference

In testing the causal inference that the presence of the justificational mode of epistemic engagement had contributed to the subsequent engagement in EEP, this research draws on the literature on collaborative engineering (Lu, 2009; Lu *et al.*, 2007; Willaert *et al.*, 1998). The literature emphasises the importance of 'rationalising' as the mechanism by which interdisciplinary collaborators seek to collectively rationalise to make rational decision in the face of uncertainty and ambiguity. Rationality, in engineering practice, is "appealing to good reason and logical arguments as well as a need to revise arguments in the light of evidence and argument" (Lucas *et al.*, 2014;p.17). 'Rationalising' is the mechanism by which engineers make simplifying assumptions in order to make subjective rational decisions and to clarify what to test in their engagement in EEP.

Evidences that the 'rationalising' mechanism operated in the case were found in the interview and the archived data.

- 1. In the interview data: Informant A recalled that after the team had tolerated ambiguity and contradictions in the knowledge claim about the impact of mechanical forces (i.e. shear stress) on cells behaviours and about the rationale behind the suggestion to replicate the art-and-craft aspects of practical knowledge (i.e. green fingers), they rationally decided on the specific analysis and test that they had conducted. [see Evidence Statement 4 & 23
- 2. In archived data: The rational analysis conducted was reported by the customer organisation that for the project they had "put a sizeable process engineering effort…into the development of automation for cell culture plants" (Fairtlough, 1989; p.592).

Since the justificational mode of epistemic engagement is necessary for the 'rationalising' mechanism to operate, and the operation of the 'rationalising' mechanism is necessary for the engagement in the EEP, the above evidence could be

treated as 'smoking gun'. Thus, the test confirms the plausibility that the justificational mode of epistemic engagement is likely to have caused the engagement in the evidential epistemic practice in the case studied.

# 5.7.4 Tracing variable #4

The pathways diagram in Figure 5.8 indicates that there is a left-out variable, which enables the engineers to overcome the perceived contributory barrier. The identification of the left-out variable uses the results of ANT analysis in the moment of 'enrolment'. There, the presence of the complemental mode of epistemic engagement, in which the engineers envisioned the benefits that could be gained from combining knowledge, is seen as influential to their subsequent engagement in the evidential epistemic practice. Therefore, the complemental mode is the suspected missing variable.

### 5.7.4.1 Identifying the variable

The identification of the complemental mode is also informed by the literature on knowledge combination, which identifies that improved performances in New Product Development, measured through process efficiency and product effectiveness, usually result from combinations of complementary knowledge (Bhatt *et al.*, 2014; Buckley & Carter, 2004). Complementary knowledge is defined as knowledge that is both related and diverse (Lofstrom, 2000), and whose value is enhanced by combination (Buckley & Carter, 1999, 2004). It is therefore inferred that, following the perception of situations in interdisciplinary interaction as contributory barriers:

- the engineers had oriented their epistemic engagement in the complemental mode to envision how the knowledge described/suggested to them could be complemented by their prior knowledge and experience, and
- the complemental mode of epistemic engagement had contributed to their engagement in the evidential epistemic practice in providing evidence for the envisioned benefits of knowledge addition.

#### 5.7.4.2 Testing the descriptive inference

In testing the plausibility that orientation in the complemental mode occurred, the researcher has located auxiliary traces left behind by such an occurrence. These traces emerged during the interviews and are supported by the relevant archived data.

- 1. During the interview, informant A recalled how the team discovered the absence of important knowledge from the practitioners' descriptions of their knowledge. [see Evidence Statement 5 in Appendix 1]
- 2. In the archived data: A presentation slide stated that the project "showed that production science has a place in cell culture" (Archer, 2012;p.3). The customer organisation published that "Extensive work on cell physiology, applying many of the approaches used in....process optimisation went on alongside with the process-engineering studies" (Fairtlough, 1989;p.592). The addition of closed-loop control to the practice of culturing cell increases process consistency and has "had significant effect on yield" (Archer & Wood, 1992;p.403).

Since the presence of the complemental mode of epistemic engagement is necessary for the above traces to have existed, the traces could be counted as 'smoking gun' evidence. Therefore, the presence of the complemental mode is confirmed on the basis of 'smoking gun' test.

### 5.7.4.3 Testing the explanatory inference

In testing the causal inference that the presence of the complemental mode of epistemic engagement contributed to subsequent engagement in the evidential epistemic practice, this research draws on the literature on knowledge combination. The literature emphasises the importance of 'envisioning' as a mechanism by which the performance improvement that can be gained from knowledge combination is articulated (Buckley & Carter, 2004), and thereby clarifying what needs to be tested.

Evidence that the 'envisioning' mechanism operated in the case were found in the interview and the archived data.

- 1. In the interview data: Informant A recalled how the team had envisioned how the addition of production science to the process knowledge could improve performance: [see Evidence Statement 5 in Appendix 1]
- 2. In the archived data: The vision of how consistency in the process could be improved based on prior experience was published in a paper, *"experience with an automated method suggests that if all the variables are very tightly controlled then predictable cell stripping always occur"* (Archer & Wood, 1992;p.403).

Since the complemental mode of epistemic engagement is necessary for the 'envisioning' mechanism to operate, and the operation of the 'envisioning' mechanism is necessary for the engineers' successful engagement in evidential epistemic practices, the above evidence could be treated as 'smoking gun' evidences. Thus, the test confirms the plausibility that the complemental mode of epistemic engagement is likely to have caused the engagement in the evidential epistemic practice in the case studied.

# 5.7.5 Tracing variable #5

The pathways diagram in Figure 5.8 indicates that engagement in the evidential epistemic practice leads to the achievement of the specific outcomes for each of the pathways, namely Pathway #2 (Evidential Adoption), Pathway #4 (Evidential Translation), Pathway #6 (Evidential Avoidance), and Pathway #7 (Evidential Addition). The identification of the left-out variable uses the results of ANT analysis in the moment of 'mobilisation'. There, the presence of a perception of what evidence would gain support from others appears to have enabled the engineers to decide how best to satisfy and gain agreement of others to the acceptance of the solution.

### 5.7.5.1 Identifying the variable

The identification of the supportive perception of evidence draws on the literature on collaborative engineering. The literature emphasises that in dealing with the

uncertainties and ambiguity arising from the lack of depth in knowledge about the sociotechnical realities, it is important to satisfy rather than to optimise features of the system under development (Lu, 2009). Thus, in the absence of complete information about those realities, it is important to perceive what evidence would be good enough to satisfy the users of the system in order to get their support in accepting, and adopting, the use of the system. It is therefore inferred that, following the EEP,

- 1. the engineers had perceived the supportiveness of the evidence in order to decide what they must demonstrate to satisfy the decision makers
- 2. the perceived supportiveness of the evidence had contributed to the achievement of the evidence-based outcomes.

### 5.7.5.2 Testing the descriptive inference

In testing the plausibility of the existence of supported perception of evidence, the researcher has located auxiliary traces left behind by its existence. These traces emerged during the interviews and are supported by the relevant archived data.

- 1. In the interview data: The engineers recalled how they implicitly perceive what evidence would satisfy the users, that is to simply try to show the workability and acceptability of the solution in a real environment, rather than to maximise the depth of their learning into analysing details about the impact of shear stress on the cells to scientifically optimise the solution. [see *Evidence Statement 4 in Appendix 1*]
- 2. In the archived data: Informant A and the customer's representative stated the kind of evidence that would perceived as important to the cell culture community of practitioners which later-on drives the worldwide diffusion of the system. "Production started within four week and the first batch ran successfully. Every batch since has been processed reliably by the robots over a period of 2 ½ years. Over a million manipulations have been carried out and contamination losses (all causes) average around 0.2% operated and maintained by existing [customer organisation] staff with no previous computer or robot system experience..."(Archer & Wood, 1992;p.402). Vogt (2002;p.50) recorded that "the system was so successful that customer installed four

manufacturing lines. Word spread across the scientific sector of the success of this automated cell growth system and soon [the company] was receiving interest from other manufacturers. One of the first enquirers was the leading US pharmaceutical company – [company B]".

Since the presence of supportive perception of evidence is necessary for the above traces to have existed, the traces could be counted as 'smoking gun' evidence. Therefore, the presence of the supportive perception on evidence is confirmed on the basis of 'smoking gun' test.

#### 5.7.5.3 Testing the explanatory inference

In testing the causal inference that the presence of perception of supportive evidence leads to the achievement of the evidence-based learning outcomes, this research has located the 'satisficing' mechanism that occurs most often when a group of people look towards a joint decision that everyone can agree on (Lu, 2009). 'Satisficing' can lead to group decisions that are "rational enough" for all practical intents and purposes, and thereby gain acceptance. This appears to limit the depth and breadth of their interdisciplinary learning and the learning outcomes as their task is to ensure the solution works.

Evidence that the 'satisficing' mechanism took place in the case is located in the interview and the archived data.

- 1. In the interview data: Informant A recalled how he satisfied the lack of depth and absence of certainty in knowledge about cell damage due to shear stress caused by the speed of movement. [see *Evidence Statement 4*]. Informant B explained an example of how satisficing can be practised when there is a lack of depth of knowledge about the complexity of cell responses. [see *Evidence Statement 24*]
- 2. In the archived data: There are requirements to be agreed and checked during the Acceptance Test, the Operational Test, and the Production Test (*see Sweeting*, 2002) and (Drake, 2011;p.28). The documented requirements clearly stated what would be the acceptable functionalities and performance the engineers should

adhere to in order to gain acceptance. This clearly communicates what *'workability'* would satisfy the end-users.

Since the perception of acceptance is necessary for the 'satisficing' mechanism to operate, and the operation of the 'satisficing' mechanism is necessary for the accomplishment of the evidence-based learning outcomes, the above evidence could be treated as 'smoking gun' evidence. Thus, the test confirms the plausibility that perception of supportive evidence is likely to lead to the achievement of the evidencebased learning outcomes.

# 5.8 Conclusion: A preliminary theoretical framework

This chapter has set out to identify useful components of a theory by analysing data from a heuristic case using a series of six analytical methods. Based on the overall findings, this chapter culminates in a preliminary theoretical framework shown in Figure 5.9 below.

The framework embodies the theoretical descriptions and explanations in terms of conceptual variables, causal relationships, and mechanisms that have been validated as subjective, but nevertheless plausible, conceptions that closely correspond to the actual reality of the case. Since the chapter did not set out to use the findings for describing and explaining the first case only but had set out instead to use them for describing and explaining the chosen sub-class of interdisciplinary learning in engineering practice, it does not summarise the findings by providing a detailed theoretical descriptions and explanations of the first case. Rather, the chapter abstracts out the conceptual variables and causal relationships from the context in which they were derived (i.e. the first case) and applies them in the next chapter, where they are subjected to further analysis – the cross-case comparison analysis – for the purpose of refining and generalising the theoretical descriptions.



Figure 5.9: Preliminary theoretical framework
# Chapter 6 Findings from cross-case analysis

# 6.1 Chapter introduction

This chapter reports the cross-case analyses, results, and findings from two case studies that are sampled purposefully from a pool of cases explored. The purpose is to further refine and generalise the preliminary theoretical framework developed in the preceding chapter 5. In line with that purpose, this chapter sets out to arrive at a contingent generalisation that is applicable across the chosen sub-class of interdisciplinary learning, rather than to arrive at a detailed description and explanation that are only applicable for the two cases.

The contents of this chapter are organised into four sections.

The first section clarifies what the chapter sets out to achieve, outlines the organisation of the chapter, and provides the backgrounds of the two interdisciplinary collaborations.

Section two justifies the selection of the two cases by showing that they are jointly sufficient for testing, refining and generalising a set of theoretical propositions.

Section three reports the analyses and the findings from testing, refining, and generalising the propositions.

Section four presents the resultant generalisation in the form of a proposed theoretical framework.

# 6.1.1 Introduction to the second case

The second case is an instance of interdisciplinary learning practices of engineers who learn the life science knowledge related to early stage bioprocess development, a set of research practices whereby life scientists conduct experiments in the labs to identify cells and operational conditions that optimise the production of biomedicines in large industrial-scale bioreactors. Those practices are especially challenging due to the intensive multi-factor statistical experimentations that are carried out using conventional scale-down tools, such as the shake flask, which poses a significant burden on the required time and effort (see Bareither and Pollard (2011) for the description of upstream workflow for bioprocess development). Therefore, there is an opportunity to improve those practices and the experimentation tools.

To address this opportunity, an interdisciplinary engineering and life sciences team in a life sciences automation company proposed to develop a novel tool, known generally as an automated micro-scale bioreactor, that is a representative scale-down of the large-scale industrial bioreactors. The bioprocess development scientists have never used or seen any representative scale-down tool since they are more familiar with using the conventional scale-down tools such as shake flasks, micro-titre plates, and bench-top bioreactors. Even though these are non-representative, they are in their domain of scientific practices as opposed to the large-scale bioreactors that are in the chemical engineering domain of practices (See Doran (2013) for the domain demarcation). Therefore, the knowledge that the scientists contributed to the collaboration is related to those conventional tools. During their 18-months interdisciplinary interactions from mid-2008 to end-2009, the engineers encountered life science knowledge related to the conventional tools while pursuing their aspiration to miniaturise the large-scale bioreactors. Three of the engineers provided the account of their interdisciplinary learning practices.

Three engineering members of the core development team were interviewed. Table 6.1 provides their anonymised names, their backgrounds, and relevant experiences.

Anonymised names	Background	Relevant prior experience
Informant D (Dalton)	Manufacturing Engineering	Developing cell culture systems
Informant E (Elton)	Software Engineering	Developing cell culture systems
Informant F (Fenton)	Telecommunication Engineering	-

Table 6.1: Engineers' details

#### 6.1.1.1 Informant D

Informant D graduated with a Master in Manufacturing Engineering Tripos (MET) from the University of Cambridge in 1992. Upon graduation, he worked for 4 years as a Consultant at a technology consulting company. He then became the Product Development Manager leading the technical aspects of new product developments. In 2008, he was tasked to come up with a concept of a micro bio-reactor. At that time, he already had 16 years of experience mainly in developing automation systems for life sciences users, working with the life sciences staff of the company. Thus, he qualifies for the 'experienced interdisciplinary engineer' category.

#### 6.1.1.2 Informant E

Informant E started his career working with an instrument company that make instruments for chemical products. After fourteen years of experience working in other instruments companies and in a software house, he joined the present company in 2002. Together with other engineers and life sciences colleagues, he had developed several systems for their life sciences customers. At the start of the studied project in 2008, he had 20 years of engineering experiences, mostly related to life science automation. Thus, he is categorised as an 'experienced interdisciplinary engineer'.

#### 6.1.1.3 Informant F

Informant F graduated in BEng Electronic, Electrical, and Communication Engineering from the University of Bath in 1997. His involvement in the project is his first assignment after joining the company in 2004. Prior to 2004 he was moving jobs between a few companies that develop software for telecommunication companies. He self-describes himself as a 'junior' in the studied project. Therefore, this research classifies him as an 'early career engineer'. At the point of the interview, he has been the software lead since 2013, responsible for architecting a number of software platforms for robotic life sciences system.

In addition to Informant D, E and F, other informants who were also interviewed include Informant G, H, I and J.

Informant G was the Business development Consultant during the project duration. At the time of the interview, he was the Director of Business development. Informant H was the Head of Engineering department at the time of the interview. He was not directly involved in the project, but was involved in a project that produced a component that was reused by the studied project. Informant I was the Chief Technology Officer. He was not directly involved in the studied project, but provided the technical leadership and direction. Informant J, was the CEO of the company since 2009 after being the CFO since 2006. All of the informants portrayed the studied project as a cornerstone to their success in life sciences automation business.

# 6.1.2 Introduction to the third case

The third case is an instance of interdisciplinary learning by engineers who learn the life science knowledge related to lung diagnostics, whereby medical practitioners diagnose lung functions. The engineers were addressing problems related to the development and commercialisation of a non-invasive lung diagnostic device. The device needs to pass various tests of safety and usability before it can be used in a hospital environment. Knowledge about safety and usability have been standardised in the form of standard requirements that are provided with detailed parameter values. The engineers need to make sure that the device conforms to those standards. The engineers collaborate with medical practitioners to develop the prototype further into usable products.

Two engineers provided accounts of their learning of the life science knowledge related to the respiratory medical practice domain. One of them has an extensive prior experience in the domain as a field service engineer. The other one had just been working for four months after graduated with a PhD in respiratory signal processing. Their background is provided in Table 6.2 below.

Table 6.2: Engineers' details

Anonymised names	Background	Relevant prior experience
Informant K (Keith)	Mechanical Engineering	Field service engineers in hospitals
Informant L (Leith)	Biomedical Engineering	PhD studies in respiratory signal analysis

Informant K is the product and operations manager at the company, a post he has held since 2012. Before that, he had more than twenty years of experience providing installation and supports within hospitals and clinics, configuring respiratory and cardiology diagnostic system. Therefore, this research classifies him as an 'experienced interdisciplinary engineer.

Informant L graduated in 2008 in BEng Telecommunications Engineering from King's College London before graduating with a PhD in Biomedial Engineering from Southampton University in 2014. He had worked part-time from 2009 to 2014, processing signals of optical diagnostics systems for a company. At the time of the interview, he had just joined the company and the project for four months. Based on his educational and work experiences in the biomedical field, this research treats him as an 'early career interdisciplinary engineer'.

# 6.2 Justification for case selection

The two interdisciplinary collaborations are purposefully sampled from a pool of cases studied to help refine and generalise the preliminary theoretical framework developed from the first case study. The selection is informed by two criteria called the 'least likely' and 'most likely' criteria. The least likely criterion is applied first to make sure that the researcher falsifies the different propositions embodied in the preliminary theoretical framework against interdisciplinary learning practices where the propositions are least likely to hold. For example, the proposition that engineers are likely to engage in consultational epistemic practice is tested against interdisciplinary learning practices where the epistemic practice is least likely to occur. After that, the most likely criterion is applied to make sure that the researcher test propositions against other interdisciplinary practices where the propositions are most likely to hold.

The next subsection 6.2.1 formulates the testable propositions. Then, subsection 6.2.2 shows how the interdisciplinary learning practices of the different engineers from the two interdisciplinary collaborations satisfy the least likely and most likely criteria.

# 6.2.1 Formulating testable propositions

Propositions are formulated in line with the two research questions of 'how engineers practise their interdisciplinary learning?' and 'why engineers engage in different epistemic practices, and achieve different learning outcomes?' when they are involved in engineering for the life sciences projects. Therefore, the propositions contain statements regarding the likelihood of practising engineers engaging in the three different categories of epistemic practices (3 propositions), and regarding how the different learning outcomes are likely to be achieved from engaging in the different epistemic practices (4 propositions). All the seven propositions are derived from the preliminary theoretical framework shown in Figure 5.9 (Section 5.8).

#### 6.2.1.1 Proposition #1: Engagement in the consultational epistemic practice

Proposition #1 relates to the CEP. Based on the first case study, which has only 'experienced engineers' who lack prior experience in engineering for the life sciences project (see Table 3.2 in Section 3.6.2), Proposition #1 states that:

"Engineers who lack prior experience in engineering for the life sciences projects are likely to engage in the consultational epistemic practice in their interdisciplinary learning practices"

The proposition is contingent upon the following condition that specifies why engineers are likely to be required to engage in the consultational epistemic practice,

Condition: Engineers lack prior experience related to the life science knowledge domain.

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experiences in engineering for the life science projects are unlikely to be required to engage in the consultational epistemic practice. Therefore, the interdisciplinary learning practices of the two engineers in the second project (Informant D and E) are considered least likely to contain the consultational epistemic practice because they are least likely to have the required condition. They are both categorised as 'experienced interdisciplinary engineers' according to Table 3.2. Thus, they are selected to falsify the proposition.

It is expected that with their extensive experiences related to the processing of biological cells, the two engineers have understood the relevant knowledge. Moreover, they were not interested in relying on the knowledge related to conventional scale-down tools used by the scientists; instead, the engineers had intended to miniaturise the large-scale industrial bioreactor system.

The above proposition is also tested against the interdisciplinary learning practices of the 'early career engineer' (Informant F) in the second project where the CEP is most likely to be required due to his lack of prior experience. Moreover, he has the more experienced team members available for consultation and for helping him orientate into the perspectival mode of epistemic engagement.

# 6.2.1.2 Proposition #2: Engagement in the translational epistemic practice

Proposition #2 relates to the TEP. Based on the first case study, which has only 'experienced engineers' who lack prior experience in engineering for the life sciences project, Proposition #2 states that:

"Engineers who lack prior experiences in engineering for the life sciences projects are likely to engage in the translational epistemic practice in their interdisciplinary learning practices"

The proposition is contingent upon the following condition that specifies why engineers are likely to engage in the epistemic practice

Condition: Engineers encounter one or more situation(s) perceived as a communication barrier

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experiences in engineering for the life science projects are unlikely to be required to engage in the translational epistemic practice for learning due to the absence of a communication barrier. Therefore, the interdisciplinary learning practices of the 'experienced interdisciplinary engineer' in the third project (Informant K) are considered least likely to contain the translational epistemic practice, and thus are selected to falsify the proposition.

It is expected that with extensive experience of working in the biomedical devices industry both as a product developer and a field service engineer, he would have understood most if not all the terminologies used in the lung functions diagnostics. Moreover, the knowledge about usability and safety of biomedical devices in hospital environments has already been translated into standardised parameters that engineers must conform to, and directly use, for testing products rather than having to translate anew.

The above proposition is also tested against the interdisciplinary learning practices of the 'early career engineering' (Informant F) in the second project where TEP is most likely to occur. He is most likely to perceive a communication barrier due to his lack of experience in both engineering and the life sciences. However, he would be likely to emulate his more experienced engineering team members in: 1) orientating his mode of engagement into the perspectival mode; 2) judging the contents and forms of knowledge that are useful for developing solution; and 3) using the representational resources available in the project as a 'representing' mechanism to successfully engage in the TEP.

#### 6.2.1.3 Proposition #3: Engagement in the evidential epistemic practice

Proposition #3 relates to the EEP. Based on the first case study, which has only experienced engineers who lack prior experience in engineering for the life sciences project, Proposition #3 states that:

"Engineers who lack prior experiences in engineering for the life sciences projects are likely to engage in the evidential epistemic practice in their interdisciplinary learning practices"

The proposition is contingent upon either one of the following conditions that specify why engineers are likely to be required to engage in epistemic practice.

- 1. Engineers have translated knowledge but are uncertain about its usefulness, or
- 2. Engineers encounter one or more situation(s) perceived as a contradictory barrier, or
- 3. Engineers encounter one or more situation(s) perceived as a contributory barrier

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experiences in engineering for the life science projects are unlikely to be required to engage in the evidential epistemic practice for learning due to the absence of the above conditions. Therefore, the interdisciplinary learning practices of the 'experienced interdisciplinary engineer' in the third project (Informant K) are considered least likely to contain evidential epistemic practice, and thus are selected to falsify the proposition.

With the standardisation of knowledge in the form of usable parameters, the engineer is the least likely to perceive uncertainty in the usefulness of the translated knowledge about the standard requirements for usability and safety of biomedical devices as these are mandatory for commercialisation. This also makes the perception of a contradictory barrier unlikely to occur.

The relatively established and standardised domain of practice expects conforming behaviour towards the established knowledge that is already provided in usable form especially when the goal is to commercialise the product. Therefore, it is considered unlikely that the engineers would orientate into the justification mode for interrogating the knowledge, or subjecting it to test in order to assess its applicability and gain evidence of its relevance to their task before adopting it. Moreover, the biomedical diagnostics field in general is a relatively matured interdisciplinary domain in terms of accepting knowledge contribution from engineering. With formal degree programmes in biomedical engineering running since the 1960's (Messler, 2004), the domain is arguably one of the least likely of all engineering for the life science interdisciplinary domain to be perceived as a barrier to contributing knowledge.

The above proposition is also tested against the interdisciplinary learning practices of the 'early career engineer' in the second project where the EEP is most likely to occur. Unlike his more experienced engineering team members, he lacks the experience to judge the usefulness of translated knowledge without requiring evidence of its usefulness from other more experienced team members. He is also likely to follow his more experienced team members in perceiving contradictory practices in the use of conventional scale-down tools that burden the practitioners. Additionally, since the scientists are more familiar with the knowledge related to the conventional tools, it is likely that there is a perceived barrier to contributing knowledge, especially as a novice in both the engineering practice and in bioprocess development.

#### 6.2.1.4 Proposition #4: Achievement of the knowledge adoption outcome

Proposition #4 relates to the knowledge adoption outcome. Based on the first case study, which has only experienced engineers who lack prior experience in engineering for the life sciences project, Proposition #4 states that:

"Engineers who lack prior experience in engineering for the life sciences projects are likely to achieve knowledge adoption by engaging in either,

- CEP only, through the consultative adoption pathway, or
- CEP followed by EEP, through the evidential adoption pathway

For the consultative adoption pathway to knowledge adoption, the proposition is contingent upon the following conditions that explain why engineers are likely to achieve the consultative adoption outcome:

1. Engineers orientate their mode of epistemic engagement in the perspectival mode which enables them to recognise an expert with whom they can consult

- 2. Engineers perceive the consultative situation as analogous to their prior experience in engineering
- 3. Engineers relate the unfamiliar knowledge to their prior knowledge

For the evidential adoption pathway to knowledge adoption, the proposition is contingent upon the following conditions that explain why engineers are likely to achieve the evidential adoption outcome:

- Engineers initially perceive one or more situation where knowledge is seen as a contradictory barrier
- The engineers orientate into the justificational mode of epistemic engagement in order to interrogate the different justifications for the knowledge used
- Based on the knowledge of different justifications, the engineers rationalise by simplifying their assumptions of what evidence is essential
- The engineers engage in evidential epistemic practices

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experience in engineering for the life science projects are unlikely to achieved knowledge adoption through the two pathways. Therefore, the interdisciplinary learning practices of the two 'experienced interdisciplinary engineers' (Informant D and E) in the second project are considered least likely to contain consultative and evidential adoption, and thus are selected to falsify the proposition.

This is mainly because they are not expected to engage in the CEP as they were not interested in relying on knowledge related to the conventional scale-down tools used by the scientists; instead, the engineers had intended to miniaturise the large-scale industrial bioreactor system.

Their learning outcomes are also the least likely to contain evidential adoption when the knowledge related to the tools are perceived as contradictory because the reuse of the knowledge is unlikely to satisfy the goal of the bioprocess community in seeking optimal conditions and cells in a more efficient and effective way.

The above proposition is also tested against the interdisciplinary learning practices of the 'early career interdisciplinary engineer' in the third project (Informant L) as it is the most likely practice to result in a consultative adoption outcome. Although he has a lack of working experience and thus is more likely to consult, he has the relevant educational background and the necessary vocabulary to understand knowledge described by the experienced others with whom he consults. He is also most likely to gain evidential adoption when encountering contradiction as he has some overlapping background with the medical practitioners, which helps him to better understand and accept the concerns of the medical practice community.

#### 6.2.1.5 Proposition #5: Achievement of the knowledge translation outcome

Proposition #5 relates to the knowledge translation outcome. Based on the first case study, which has only experienced engineers who lack prior experience in engineering for the life sciences project, Proposition #5 states that:

"Engineers who lack prior experience in engineering for the life sciences projects are likely to achieve the knowledge translation outcome by engaging in either,

- CEP followed by the TEP, through the mediated translation pathway, or
- CEP followed by the TEP, and then the EEP, through the evidential translation pathway

For the mediated translation pathway to knowledge translation, the proposition is contingent upon the following conditions that explain why engineers are likely to achieve the mediated translation outcome:

- Engineers encounter one or more situation(s) perceived as a communication barrier
- Engineers orientate their interdisciplinary interaction into the perspectival mode of epistemic engagement which enables them to look at knowledge descriptions from both the engineering perspective and the life science users' perspectives,

thereby recognising the importance of sustaining the involvement of their collaborators in redefining the knowledge into engineering terms

- Engineers capitalise on representational resources such as their representing skills (drawing, creating prototypes and models) to mediate interaction, and material artefacts that represent their understanding of the life sciences knowledge to others – and enable their life science counterparts to contribute to their translational efforts.
- They are certain about the usefulness of the translated knowledge

For the evidential translation pathway to knowledge translation, the proposition is contingent upon the following additional conditions that explain why the engineers are likely to achieve the evidential translation outcome:

- They perceive uncertainty in the usefulness of the translated knowledge
- They engage in evidential epistemic practice

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experience in engineering for the life science projects are unlikely to achieved knowledge translation through the two pathways. Therefore, the interdisciplinary learning practices of the 'experienced interdisciplinary engineer' in the third case (Informant K) are considered least likely to contain the knowledge translation outcomes since he is considered the least likely to engage in TEP.

The above proposition is also tested against the interdisciplinary learning practices of the 'early career engineer' in the second project where TEP is most likely to occur. Likewise, for the evidential translation, he is also most likely to require, and to be provided, evidence to see that knowledge translation works.

# 6.2.1.6 Proposition #6: Achievement of the knowledge avoidance outcome

Proposition #6 relates to the knowledge avoidance outcome. Based on the first case study, which has only experienced engineers who lack prior experience in engineering for the life sciences project, Proposition #6 states that:

"Engineers who lack prior experience in engineering for the life sciences projects are likely to achieve the knowledge avoidance by engaging in either,

- TEP after CEP, through the mediated avoidance pathway, or
- EEP after CEP, through the evidential avoidance pathway

For the mediated avoidance pathway to knowledge avoidance, the proposition is contingent upon the following conditions that explain why the engineers achieve the mediated avoidance outcome:

#### Conditions:

- Engineers encounter one or more situation(s) perceived as a communication barrier
- Engineers orientate their interdisciplinary interaction into the perspectival mode of epistemic engagement which enables them to look at knowledge descriptions from both the engineering perspective and the life science users' perspectives, thereby recognising the importance of gaining their agreement to avoiding the knowledge they describe
- Engineers capitalise on representational resources, such as their representing skills (drawing, creating prototypes and models), to mediate interaction, and material artefacts that represent their understanding of how avoiding knowledge is useful
- They are certain about the usefulness of avoiding the knowledge

For the evidential avoidance pathway to knowledge avoidance, the proposition is contingent upon the following additional conditions that explain why the engineers achieve the evidential translation outcome:

- They perceived uncertainty in the usefulness of the translated knowledge
- They engaged in evidential epistemic practice

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experience in engineering for the life science projects are unlikely to achieve knowledge avoidance through the two pathways. Therefore, the interdisciplinary learning practices of the 'experienced interdisciplinary engineer' in the third project are least likely to contain knowledge avoidance since he is least likely to perceive situations as a communication barrier. Since knowledge of respiratory medicine is essential and the knowledge of usability and safety aspects are mandatory for commercialisation purpose, it is unlikely that he seeks to avoid the knowledge. Likewise, he is the least likely to avoid knowledge through the evidential pathway too because he is certain about the usefulness of the knowledge.

The above proposition is also tested against the interdisciplinary learning practices of the 'experienced interdisciplinary engineers' in the second case as they are most likely to contain knowledge avoidance through mediated avoidance pathway. The solution they proposed sought to supplant the conventional method of performing bioprocess development experimentation. Likewise, their learning outcomes are most likely to also contain evidential avoidance as the avoidance of some of the existing knowledge requires evidence to show that such avoidance improves practice.

#### 6.2.1.7 Proposition #7: Achievement of the knowledge addition outcome

Proposition #7 relates to the knowledge addition outcome. Based on the first case study, which has only experienced engineers who lack prior experience in engineering for the life sciences project, Proposition #7 states that:

"Engineers who lack prior experience in engineering for the life sciences projects are likely to achieve the knowledge addition outcome by engaging in CEP followed by EEP through the evidential addition pathway"

The proposition is contingent upon the following conditions that explain why engineers are able to achieve the evidential addition outcome:

- 1) When engineers perceived a contributory barrier, they orientate their mode of epistemic engagement into the complemental mode
- 2) They envision and articulate how knowledge combination would lead to performance improvement
- 3) They seek to satisfy by perceiving what evidence would gain support for knowledge addition

The above proposition has a risky prediction that can be falsified. It inherently predicts that engineers who have extensive prior experience in engineering for the life science projects are unlikely to achieved knowledge addition outcome through the evidential addition. Therefore, the interdisciplinary learning practices of the 'experienced interdisciplinary engineer' in the third project are considered as least likely to contain knowledge addition through the evidential addition pathway. The biomedical diagnostics field in general is a relatively mature interdisciplinary domain in terms of accepting knowledge contribution from engineering. It is arguably one of the least likely of all engineering for the life science interdisciplinary domains to be perceived as a barrier to contributing knowledge.

The above proposition is also tested against interdisciplinary learning practices. The 'experienced interdisciplinary engineers' in the second case are considered as the most likely to contain the knowledge addition outcome through the evidential addition pathway. They are the most likely to encounter a contributory barrier as they had intended to introduce new tools that are unfamiliar to the life science practitioners. Nevertheless, with their prior experience of encountering such barriers they are the most likely to orientate into the complemental mode of epistemic engagement, to envision and articulate how adding knowledge would improve performance, and to know how to satisfy the life science users.

# 6.2.2 Mapping requirements to case selection

Table 6.3 shows that the learning practices of the engineers in the second and third case studies are jointly sufficient for testing the seven propositions with various practices where the propositions are least-likely and most-likely to hold.

Droposition Number	Critorio	C 222 #2	C 222 #2
Proposition Number	Chiena	Case #2	Case #3
D	1		
Proposition #1	Least likely	v-experienced	-
		interdisciplinary engineers	
(CEP)			
	Most likely	$\sqrt{-}$ early career engineer	-
Proposition #2	Least likely	-	√-experienced
	,		interdisciplinary engineer
(TEP)			1 5 5
( )	Most Likely	$\sqrt{-early}$ career engineer	_
	MOOL EIKOLY	v carry bareer engineer	
Proposition #3	Least likely		1 experienced
	Least likely	-	v-experienced
			interdisciplinary engineer
(EEP)		· · · · · ·	
	Most likely	√- early career engineer	-
Proposition #4	Least likely	$\sqrt{-}$ experienced engineers	-
(Knowledge Adoption)	Most likely	-	$\sqrt{-early career}$
			interdisciplinary engineer
Proposition #5	Least likely	-	√-experienced
			interdisciplinary engineer
(Knowledge Translation)			
(Innowiedge Translation)	Most likely	v early career engineer	
	WOSt-likely		-
Drenseitien #C	Leastlikely		
Proposition #6	Least likely	-	v-experienced
			interdisciplinary engineer
(Knowledge Avoidance)			
	Most-likely	√-experienced engineers	-
Proposition #7	Least likely	-	√-experienced
			interdisciplinary engineer
(Knowledge Addition)			
	Most-likely	√-experienced engineers	-
			1

#### Table 6.3: Coverage of the proposition testing

In addition, the sample of engineers cover the required variation in experience level as shown in Table 3.2 and reproduced in Table 6.4 below.

Table 6.4: Variation in level of experiences of practising engineers

		Experience in life science domain	
		Low	High
Experience in engineering practice domain	High	Experienced engineers √-informant A & B	Experienced interdisciplinary engineers √ - informant D. E & K

Low	Early career engineers	Early career interdisciplinary engineers
	$\sqrt{-}$ informant F	- informant L

Thus, there are total of seven engineers whose learning practices are analysed for developing, refining, and generalising the preliminary theoretical framework across the whole sub-class.

The next section details out the testing for each of the seven propositions.

# 6.3 Proposition testing and results

# 6.3.1 Testing proposition #1

Proposition #1 is first tested with the learning practices of the two experienced interdisciplinary engineers in the second project since their learning practices have been determined in section 6.2.1 as the least likely practice to involve engagement in the CEP. The test finds that proposition #1 is falsified since the engagement in the CEP was found in their learning practices. This falsification enables the generalisation of the engagement in CEP across the whole subclass based on the logic that if the CEP occurs even where it is least likely expected to occur, then it is likely to occur elsewhere within the chosen sub-class also.

To verify that the generalisation is valid, it is then checked with the learning practices of the early career engineer in the second project. Since his learning practices have been determined as the most likely practice to involve engagement in the CEP, the generalisation must apply to his learning practices. Failure to locate CEP in his learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since CEP is found in his learning practices.

The following two subsection reports the testing and its results.

#### 6.3.1.1 Generalisation of the CEP

Proposition #1 implicates that the two experienced engineers in the second case (Informant D and E) are least likely to engage in the CEP on the basis that they both have extensive prior experience in engineering for the life sciences projects relevant to the studied project. However, an unexpected engagement in the CEP occurred during their interaction with their life science collaborators who were interested to know if the novel scale-down tools that the team were developing could also be used to support other scientific practices for which the tool was not originally designed.

Since the engineers had conceived the novel idea for specific requirements related to the experimental determination of optimal cells and operating conditions, they were not aware of these other practices, such as developing feed and media strategies. Rather than dismissing the unexpected interest as irrelevant to the on-going development of the original product concept, the engineers engaged instead in the CEP in order to know more about these other practices. As a result, they developed understanding of these other practices. This learning enables them to incorporate additional features to the original concept, and thereby producing a family of related products.

The empirical traces of the occurrence of this CEP emerged during the interviews as well as being evident in a number of archived press releases about a series of additional features and different versions of the tool that are related to the engagement in CEP.

Interview data: Informant E recalled how he learnt about the other practices consultatively from their life sciences counterparts. [see Evidence Statement 25 in Appendix 1]

In archived data: The researcher keeps a compilation of the relevant press releases published between February 2010 to July 2014 about a series of additional features and different versions of the tool that are related to the engagement in CEP. These were accessible from the company's webpage until they were removed following the company's acquisition. Additionally, other publications including relevant scientific journals and patent applications are also located and kept as evidence. The above evidence of the engagement in the CEP is theoretically important because the learning practices in which it was found are considered as least likely to contain the CEP. First, it falsifies proposition #1, which proposes that only engineers who lack experience in engineering for the life sciences projects are likely to engage in consultational epistemic practice. Therefore, the proposition is revised to include also engineers with extensive experience in engineering for the life sciences projects.

Secondly, it enables this research to contingently generalise that the CEP is likely to occur across all learning practices of engineers who collaborate in engineering for the life sciences projects on the condition that they encounter situations in interdisciplinary interactions that make them perceive an insufficiency in their prior knowledge. Additionally, the findings show that engineers are able to overcome this perceived insufficiency by orientating their mode of epistemic engagement into the perspectival mode that would enable them to see the importance of the knowledge from the life sciences users' perspective and recognise the right expertise from whom they could learn consultatively.

Thus, proposition #1 is revised and generalised as:

"Engineers collaborating in engineering for the life sciences projects are likely to engage in consultational epistemic practice." The condition for which the proposition holds is "when engineers perceive an insufficiency in their prior knowledge." The enabling factor appears to be the orientation into the perspectival mode of epistemic engagement.

#### 6.3.1.2 Checking the generalisation of the CEP

The generalisation is checked with the learning practices of the early career engineer in the second project (Informant F) since his learning practices have been determined as most likely to involve engagement in the CEP. This checking verifies the generalisation since CEP was practised by him as provided in his interview. [see Evidence Statement 26 in Appendix 1]

On the other hand, it is also found that in the least likely learning practice, there is an engagement in a category of epistemic practice that could not be categorised as any of the three categories of epistemic practice embodied in the preliminary theoretical framework. This deviant finding is nevertheless theoretically important for enriching and refining the evolving theoretical framework.

#### 6.3.1.3 The deviation from the CEP

The epistemic practice that deviates from the preliminary framework occurred when the engineers were provided with a suggestion to consider the adoption of knowledge related to the conventional tools with which the life scientists are more familiar. However, the design engineer was resolute in his prior knowledge that scale-down tools should be representative of the large-scale bioreactor. Therefore, he used his prior knowledge in dealing with the suggestions. [see Evidence Statement 27 in Appendix 1]

The excerpt in Evidence Statement 27 is interpreted as containing a set of actions that constitute an epistemic practice of comparing the knowledge-based suggestion against a set of criteria that is underpinned by the prior knowledge (i.e. of the features of the large-scale bioreactors). The actions include comparing features against certain criteria/requirement, judging the extent to which the suggestions would satisfy the criteria, and predicting how the suggestions would fare in the future if they were accepted. These actions are conceptualised as Comparative Epistemic Practice, the fourth category of epistemic practice abbreviated hereafter as CPEP.

The explanation for this practice is based on the interview excerpt by Informant D that says "*if you're going to make an assessment of what is good about something on the market, then you might look at say a shake flask system and typically they do not have individual pH control, or dissolved oxygen control and so you say well that's not good from the process point view.*".

It is interpreted that CPEP is caused by a prior orientation into a mode of epistemic engagement conceptualised as the Evaluational Mode. In this mode, the learner is orientated towards engaging with the knowledge encountered by evaluating the knowledge in order to judge and decide whether to commit to learning it further for adoption, or for avoiding its inclusion in the solution.

However, this CPEP appears to be necessarily contingent in the situation "when engineers perceive sufficiency in their prior knowledge." This is because the practice appears to be absent from their early career engineer team member, who is likely to have insufficient prior engineering knowledge with which he could compare. Since knowledge suggestions tend to occur in interdisciplinary collaboration and evaluation of their relevance to the problems at hand are necessary, this deviant finding can be generalised contingently.

Thus, a new generalised contingent proposition is formulated:

"Engineers collaborating in engineering for the life sciences projects are likely to engage in comparative epistemic practice." The condition for which the proposition holds is "when engineers perceive sufficiency in their prior knowledge." The enabling factor appears to be the evaluational mode of epistemic engagement.

# 6.3.2 Testing proposition #2

Proposition #2 is first tested with the learning practices of the experienced interdisciplinary engineer in the third project since they have been determined in subsection 6.2.1.2 as the least likely practice to involve engagement in TEP. The test finds that proposition #2 is falsified since the engagement in the TEP was found in his learning practices. This falsification enables the generalisation of engagement in TEP across the whole subclass based on the logic that if TEP occurs even where it is least likely to occur, then it is likely to occur elsewhere within the chosen sub-class.

To verify that the generalisation is valid, it is checked with the learning practices of the early career engineer in the second project. Since his learning practices have been determined as the most likely practice to involve engagement in TEP, the generalisation must apply there. Failure to locate TEP in his learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since TEP is found in his learning practices.

The following two subsection reports the testing and its results.

#### 6.3.2.1 Generalisation of the TEP

Proposition #2 implies that the experienced interdisciplinary engineer in the third project is least likely to engage in the TEP on the basis that the relevant knowledge already exists in the content and forms that are directly usable for developing solutions and for conforming to standard requirements. In particular, the knowledge of lung function is typically extensively parameterised in spirometry and the knowledge of usability and safety of biomedical devices are typically standardised in quantitative terms by regulatory authorities. However, an unexpected engagement in the TEP occurred during his dealing with the IEC 60601 standards. The standard requirement for "movement over threshold" had provided quantitative figures of 20mm that was perceived as a "technical failure".

Since the engineer perceived that the quantitative figure is not informative for designing wheels that would allow the product to pass the 20mm test, he resorted to 'design around' the requirement. Like many others who also reportedly were having trouble conforming to the 20mm threshold with small wheels, the engineer specified a bigger wheel size that corresponds to a higher threshold (33cm) so that the product could easily pass the test albeit with bigger wheels.

The empirical traces of the occurrence of this TEP emerged during the interviews as well as being evident in a number of online discussion forums about the difficulties in conforming to the requirement. Additionally, archived records showed that the requirement was eventually amended and the 20mm figure was replaced with a 10mm threshold.

Interview data: Informant K recalled how he was engaging in the TEP. [see Evidence Statement 28 in Appendix 1]

In archived data:

 There are many online communities of medical cart designers that discuss their struggles to translate the 20mm threshold figure into appropriate wheel size and their eventual relief after it was amended. For example, this online forums published on <u>https://www.ptcusercommunity.com/thread/39906</u> and also a relevant blog on <u>http://www.medicalcarts.org/blog/how-do-you-get-a-medical-</u> <u>cart-up-and-over-a-20mm-threshold</u>

2) The empirical traces of the standards and the amendment and can be accessed from the IEC webpage at <u>https://webstore.iec.ch/publication/2606</u> (the 20mm threshold) and at <u>https://webstore.iec.ch/publication/2612</u> (the amendment).

The above evidence of the engagement in TEP is theoretically important because the learning practices in which it was found are considered as least likely to contain TEP. First, it falsifies proposition #2, which proposes that only engineers who lack experience in engineering for the life sciences projects are likely to engage in the TEP. Therefore, the proposition is revised to include also engineers with extensive experience in engineering for the life sciences projects.

Secondly, it enables this research to contingently generalise that the TEP is likely to occur across all learning practices of engineers who collaborate in engineering for the life sciences projects on the condition that 1) they encounter situations in interdisciplinary interactions that they perceive as a form of communication barrier, and that 2) they overcome this perceived insufficiency by orientating their mode of epistemic engagement into the perspectival mode that would enable them to view the problem from an engineering perspective. This enables them to resort to analysis for arriving at the precise and more useful values. Thus, proposition #2 is revised and generalised as:

"Engineers collaborating in engineering for the life sciences projects are likely to engage in translational epistemic practice." The condition for which the proposition holds is "when engineers encounter one or more situation(s) perceived as a communication barrier". The enabling factor appears to be the perspectival mode of epistemic engagement that capitalises on engineering experience and knowledge in engineering analysis.

#### 6.3.2.2 Checking the generalisation of TEP

The generalisation is checked with the learning practices of the early career engineer in the second project since he has been determined as the most likely to engage in TEP. This checking verifies the generalisation since TEP was practised by him as provided in his exemplary interview. [see Evidence Statement 29 in Appendix 1]

# 6.3.3 Testing proposition #3

Proposition #3 is first tested with the learning practices of the experienced interdisciplinary engineer in the third project since he has been determined in subsection 6.2.1.3 as the least likely to engage in EEP. The test finds that proposition #3 is falsified since engagement in EEP was found in his learning practices. This falsification enables generalisation of engagement in EEP across the whole subclass based on the logic that, if the EEP occurs even where it is least likely expected to occur, then it is also likely to occur elsewhere within the chosen sub-class.

To verify that the generalisation is valid, it is checked with the learning practices of the early career engineer in the second project. Since his learning practices have been determined as the most likely practice to involve engagement in EEP, the generalisation must apply to his learning practices. Failure to locate EEP in his learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since EEP was found in his learning practices. Finally, the examination of the practices by the other engineers reinforces this generalisation since they also practise EEP albeit under various different contingencies.

The following two subsections report the testing and its results.

#### 6.3.3.1 Generalisation of the EEP

Proposition #3 implies that the experienced interdisciplinary engineer in the third project is least likely to engage in the EEP on the basis that the standards requirements

that an international regulatory body had imposed are meant to be adopted. However, an unexpected engagement in EEP occurred during their interaction with the IEC 60601 standards. The standard requirement for "movement over threshold" had provided quantitative figures of 20mm that was perceived as a "technical failure" after experiencing and seeing the evidence of its failure in a real operating environment.

The empirical traces of the occurrence of this EEP emerged during the interviews. Additionally, archived records showed that the test was eventually amended and the 20mm figure was replaced with 10mm threshold.

Interview data: Informant K recalled how he was engaging in the EEP. [see Evidence Statement 30 in Appendix 1]

The above evidence of the engagement in the EEP is theoretically important because the learning practices of the knowledge about safety standards in which it was found are considered as the least likely to contain EEP. First, it falsifies proposition #3, which proposes that only engineers who lack experience in engineering for the life sciences projects are likely to engage in the EEP. Therefore, the proposition is revised to also include engineers with extensive experience in engineering for the life sciences projects.

Secondly, it enables this research to contingently generalise that EEP is likely to occur across all learning practices of engineers who collaborate in engineering for the life sciences. It appears to have various contingencies. However, EEP is a practice that can emerge under various different contingencies that requires evidence that a solution works.

#### 6.3.3.2 Checking the generalisation of the EEP

The generalisation is checked with the learning practices of the early career engineer in the second project since his learning practices have been determined as the most likely to involve engagement in the EEP. This checking verifies the generalisation since EEP was practised by him as provided in his accounts on integration testing. [see Evidence Statement 31 in Appendix 1]

# 6.3.4 Testing proposition #4

Proposition #4 is first tested with the learning practices of the two experienced interdisciplinary engineers in the second project since their learning practices have been determined in sub-section 6.2.1.4 as least likely to involve achievement of the knowledge adoption outcome through both consultative adoption and through evidential adoption. The test finds that proposition #4 is falsified since the achievements of the knowledge adoption outcome through both pathways were found in their learning practices. This falsification enables the generalisation of the achievement of the knowledge adoption outcome across the whole subclass based on the logic that if it occurs even where it is least likely expected to occur, then it is also likely to occur elsewhere within the chosen sub-class.

To verify that the generalisation is valid, it is checked with the learning practices of the early career interdisciplinary engineer in the third project. Since his learning practices have been determined as most likely to involve achievement of the knowledge adoption outcome, the generalisation must apply there. Failure to locate knowledge adoption in his learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since the knowledge adoption outcome is found in his learning practices. Finally, the examination of the practices of the other engineers reinforces this generalisation since they also achieve knowledge adoption.

The following two subsection reports the testing and its results.

# 6.3.4.1 Generalisation of the knowledge adoption outcome.

Proposition #4 implies that the two experienced interdisciplinary engineers in the second project are least likely to achieve knowledge adoption on the basis that they set out to develop a scale-down tool that differs fundamentally from the existing scale-down tools used by the life scientists. Also, the engineers were already familiar with those tools such as shake flasks and micro-titre plates, having developed other systems that

make use of those tools in the past and understood their limitations. They have also worked with systems that handle mammalian cells for many years and understand how to look after them. However, an unexpected engagement in CEP occurred during their interaction with their life science collaborators who were interested to know if the novel scale-down tools that the team were developing could also be used to support other scientific practices and other cell-types, such as the microbial cells, for which the tool was not originally designed. It has been shown in section 6.3.1.1 that they had engaged in consultation and developed understanding of the other practices and how to deal with microbial cells.

The empirical traces of the achievements emerged during the interviews as seen earlier in section 6.3.1.1 from Informant D. Additionally, archived records showed the need to incorporate the requirement for microbial cells.

Interview data: Informant D recalled how the microbial version of the product was conceived [see Evidence Statement 32 in Appendix 1]

The above evidence of achievement in knowledge adoption through the consultative adoption pathway as well as through the evidential adoption pathway is theoretically important because the learning practices of the two engineers are considered as least likely to contain the achievement of knowledge adoption through those pathways. First, it falsifies proposition #4, which proposes that only engineers who lack experience in engineering for the life sciences projects are likely to achieve knowledge adoption outcomes through those pathways. Therefore, the proposition is revised to include engineers with extensive experience in engineering for the life sciences projects.

Secondly, it enables this research to contingently generalise that the knowledge adoption outcomes through those pathways are likely to occur across all learning practices of engineers who collaborate in engineering for the life sciences.

Thirdly, the above accounts help refine the evolving framework with more pathways because the prior cause of engagement in the evidential epistemic practice could not be categorised as any of the four situational perceptual variable – analogous perception – since microbial cells were not perceived as analogous to mammalian cells in their requirements, or communication barrier – since they were able to understand the

relevant biological terms, or contradictory barrier – since they did not observe any discordant practice or provided with ambiguous knowledge claims, or contributory barrier - since they did not perceived any barrier to adding knowledge.

Rather, the implications of the new cells for the changes to the original system were not clear to both the engineers and their life science counterparts. The latter knew about the cells' behaviours but did not know all the implications for the changes the engineers needed to make. Thus, there is an absence of knowledge from both parties about the implications of the knowledge to the solutions. This is conceptualised as the implicational barrier.

Despite this barrier, the engineers seek to know the implications of the changes. This is conceptualised as the Implicational mode of epistemic engagement. To know the implication in the absence of an established theory, experimentation appears to enable the engineer to assemble evidence to support their learning about the cells requirements and the corresponding implications that these have on the original system, thus achieving a solution that satisfies the microbial cells and the users.

Therefore, as well as generalising the knowledge adoption outcomes, the pathways are enriched with another contingent pathway to adoption called the Implicational adoption pathway.

#### 6.3.4.2 Checking the generalisation

The generalisation is checked with the learning practices of the early career interdisciplinary engineer in the third project since his learning practices have been determined as most likely to involve achievement of the knowledge adoption outcome. This checking verifies the generalisation since the knowledge adoption outcomes were achieved by him as detailed in his accounts [see Evidence Statement 33 in Appendix 1]

# 6.3.5 Testing proposition #5

Proposition #5 is first tested with the learning practices of the experienced interdisciplinary engineer in the third project since they have been determined in sub-

section 6.2.1.5 as least likely to involve achievement of the knowledge translation outcome through both mediated translation and through evidential translation. The test finds that proposition #5 is falsified since the achievement of a knowledge translation outcome was found in his learning practices. This falsification enables the generalisation of the achievement of the knowledge translation outcome across the whole subclass based on the logic that if it occurs even where it is least likely expected to occur, then it is also likely to occur elsewhere within the chosen sub-class.

To verify that the generalisation is valid, it is checked with the learning practices of the early career interdisciplinary engineer in the second project. Since his learning practices have been determined as most likely to involve achievement of knowledge translation outcomes, the generalisation must apply to his learning practices. Failure to locate knowledge translation in his learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since the knowledge adoption outcome is found in his learning practices. Finally, the examination of the practices of the other engineers reinforces this generalisation since they also achieve knowledge translation

The following two subsection reports the testing and its results.

# 6.3.5.1 Generalisation of knowledge translation outcome

Proposition #5 implies that the experienced interdisciplinary engineer in the third project is least likely to achieve knowledge translation on the basis that relevant knowledge already exist in parameterised forms to be used. As seen in section 6.3.2, the engineer did achieve the knowledge translation outcome by deriving different values due to a communication barrier that was perceived by the failure of the 20mm threshold standard. However, the pathway here is the evidential pathway since the usefulness of the derived knowledge is not certain until the relevant evidence is seen. The other pathway to knowledge translation without evidence is when they interact with medical devices and biological parts, which only provide signals and signs, thus they have to interpret the outputs of those medical devices in terms of what they mean.

The above evidence of achievement in knowledge translation is theoretically important because the learning practices of the engineer was considered as least likely to contain the achievement of knowledge translation outcome resulting from a communication barrier. First, it falsifies proposition #5, which proposes that only engineers who lack experience in engineering for life sciences projects are likely to achieve knowledge translation outcomes through those pathways. Therefore, the proposition is revised to also include engineers with extensive experience in engineering for the life sciences projects.

Secondly, it enables this research to contingently generalise that the knowledge translation outcome through those pathways are likely to occur across all learning practices of engineers who collaborate in engineering for the life sciences.

#### 6.3.5.2 Checking the generalisation

The generalisation is checked with the learning practices of the early career engineer in the second project since they have been determined as most likely to involve achievement of knowledge translation. This checking verifies the generalisation since knowledge translation was achieved by him as provided in his account. [see Evidence Statement 34 in Appendix 1]

# 6.3.6 Testing proposition #6

Proposition #6 is first tested with the learning practices of the experienced interdisciplinary engineer in the third project since they have been determined in subsection 6.2.1.6 as least likely to involve achievement of the knowledge avoidance outcome through both mediated avoidance and through evidential avoidance pathways. The test finds that proposition #6 is falsified since the achievement of a knowledge avoidance outcome was found in his learning practices. This falsification enables the generalisation of the achievement in knowledge avoidance outcome across the whole subclass based on the logic that if it occurs even where it is least likely expected to occur, then it is also likely to occur elsewhere within the chosen sub-class.

To verify that the generalisation is valid, it is checked with the learning practices of the two experienced interdisciplinary engineers in the second project. Since their learning practices have been determined as most likely to involve achievement of knowledge avoidance outcome, the generalisation must apply to their learning practices. Failure to locate knowledge avoidance in their learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since the knowledge avoidance outcome was found in his learning practices. Finally, the examination of the practices by the other engineers reinforces this generalisation since they also achieve knowledge avoidance

The following two subsection reports the testing and its results.

#### 6.3.6.1 Generalisation of the knowledge avoidance outcome

Proposition #6 implies that the experienced interdisciplinary engineer in the third project is least likely to achieve knowledge avoidance outcome on the basis that knowledge already exists in parameterised forms to be used. As seen in section 6.3.2, the engineer did achieve the knowledge avoidance outcome by 'designing around' the standard 20mm threshold, which was perceived, and eventually proven, as a "technical failure". Following the revelation that the bigger wheel was also futile, the knowledge was avoided.

#### 6.3.6.2 Checking the generalisation

The generalisation is checked with the learning practices of the experienced interdisciplinary engineer in the second project (Informant D) since they have been determined as most likely to involve achievement of the knowledge avoidance. This checking verifies the generalisation since knowledge avoidance was achieved by him as provided in his account. [see Evidence Statement 35 in Appendix 1]

# 6.3.7 Testing proposition #7

Proposition #7 is first tested with the learning practices of the experienced interdisciplinary engineer in the third project since he has been determined in subsection 6.2.1.7 as the least likely to involve achievement of the knowledge addition through the evidential addition pathway. The test finds that proposition #7 is falsified since the achievement of knowledge addition outcome through evidential addition was found in his learning practices. This falsification enables the generalisation of the achievement of the knowledge addition outcome across the whole subclass based on the logic that if it occurs even where it is least likely expected to occur, then it is likely to occur elsewhere within the chosen sub-class also.

To verify that the generalisation is valid, it is checked with the learning practices of the two experienced interdisciplinary engineers in the second project. Since their learning practices have been determined as most likely to involve achievement of knowledge addition outcome, the generalisation must apply to their learning practices. Failure to locate knowledge addition in their learning practice will cast doubt on the generalisation and falsify it. The checking did not manage to falsify it since knowledge addition outcome is found in their learning practices.

The following two subsection reports the testing and its results.

#### 6.3.7.1 Generalisation of the knowledge addition outcome

Proposition #7 implies that the experienced interdisciplinary engineer in the third project is least likely to achieve the knowledge addition outcome through the evidential addition pathway on the basis that the biomedical diagnostics field in general is a relatively matured interdisciplinary domain in terms of accepting knowledge contribution from engineering. It is arguably one of the least likely of all the engineering for the life science interdisciplinary domains to be perceived as a barrier to contributing knowledge. However, the data shows that this acceptance of contribution does not mean that there is no need to show evidence that adding new knowledge actually improves performance, as expressed by Informant K. [see Evidence Statement 36 in Appendix 1].

#### 6.3.7.2 Checking the generalisation

The generalisation is checked with the learning practices of the experienced interdisciplinary engineer in the second project since he has been determined as the most likely to involve achievement of the knowledge addition. This checking verifies the generalisation since knowledge addition was achieved as provided in the interview with Informant D. [see Evidence Statement 37 in Appendix 1]

This test completes all the tests and the revisions of the propositions. The revised propositions and the associated findings then inform the evolution of the preliminary theoretical framework into a contingent theoretical framework that is generalised over the whole sub-class.

# 6.4 Conclusion: The contingent generalisation of the theoretical framework

This chapter has set out to arrive at a contingent generalisation that is applicable across the chosen sub-class of interdisciplinary learning by subjecting the preliminary theoretical framework to cross-testing with data from two interdisciplinary projects. Based on the overall findings, this chapter culminates in a generalised contingent theoretical framework shown in Figure 6.1.



Figure 6.1: Generalised theoretical framework

The theoretical framework embodies contingent descriptions and explanations of the phenomenon of interdisciplinary learning in engineering practice for the sub-class of engineering for the life sciences collaboration.

The description recognises that practising engineers are likely to participate in an engineering for the life science collaboration with different knowledge profiles. In such a collaboration, they are likely to encounter knowledge suggestions made by their life sciences collaborators. During that encounter, they are likely to respond to the knowledge suggestions based on their perception of whether or not they have sufficient knowledge to engage with the knowledge suggestion. This situational perception is represented by the theoretical variable called "perceived sufficiency in prior knowledge". The theoretical framework embodies two likely situational perceptions and the two corresponding ways of learning through epistemic practices.

First, when engineers perceive an insufficiency in prior knowledge, they are more likely to engage in consultational epistemic practice, the likelihood of which is increased by the presence of an intervening variable conceptualised as the perspectival mode of epistemic engagement.

Second, when engineers perceive sufficiency in prior knowledge, they are more likely to engage in the comparative epistemic practice in making comparison between the knowledge suggestion and their own prior knowledge that they use as a criteria for evaluating the knowledge suggestion. The likelihood of engaging in the practice is increased by their orientation into the evaluational mode of epistemic engagement.

The subsequent learning practice after these two engagements is contingent upon situations in their interdisciplinary interactions and upon how they perceive those interactions. The findings identify and explore five different perceptions that are represented by the presence of five situational perceptual variables.

First, engineers may perceive situations as analogous to their prior experience. Second, engineers may perceive one or more of those situations as a communication barrier. Third, they may perceive them as a contradictory barrier. Fourth, they may perceive
them as a contributory barrier, and fifth, they may perceive them as an implicational barrier.

When engineers perceive the situations as analogous to their prior experience, they are more likely to acquire the new knowledge provided in those situations. The likelihood is enabled by relating the new knowledge to their prior knowledge. Thus, the sterility of the cell culturing practice is related to chip manufacturing, and roller-bottle cell culture method is related to emptying and filling in bottles. Hence, learning is likely to achieve the adoption of the details of the similar aspects.

On the other hand, when engineers perceived one or more situations as a communication barrier, they are more likely to engage in translational epistemic practice to translate the knowledge they encounter into different contents and forms that enable them to proceed with their task. The likelihood is enabled by their orientation into the perspectival mode.

In other situations perceived as either a contradictory barrier, or a contributory barrier, or an implicational barrier, they are more likely to engage in the evidential epistemic practices, enabled, respectively, by their orientation into justificational mode, complemental mode, or implicational mode of epistemic engagement.

The above descriptions describe and explain how and why those four epistemic practice emerge in interdisciplinary learning in engineering practice within the engineering for the life sciences projects.

For describing and explaining the learning outcomes, the findings identify nine contingent pathways to four different learning outcomes, all of which are represented in the theoretical framework as uninterrupted chains of cause-and-effect relationships between theoretical variables.

With the development of the theoretical framework, it is timely to discuss on how it addresses the knowledge requirements that drive this research. This is discussed in the next chapter.

# **Chapter 7 Discussion**

# 7.1 Introduction

This chapter discusses the research findings from the theoretical and methodological perspectives. From the theoretical perspective, the discussion compares and contrasts the findings with the extant theories and literature in order to position the findings within the existing bodies of knowledge. This will determine whether the findings can provide reinforcement, refinement, or revision of the current knowledge.

From the methodological perspective, the discussion centres on the ways in which the research methodology has contributed to increasing the quality of the results. It also discusses some limitations of the methodology.

By synthesising the findings, this chapter ends with the summary of the key insights gained from the theoretical and methodological discussions. These key insights enable the conclusion chapter to draw out the practical implications of this research.

# 7.2 Theoretical discussion

This section discusses the findings in relation to the extant theories and literature while suggesting the reinforcements, refinements, or revisions to them.

The main findings that constitute the theoretical framework can be divided into five sets:

- 1. Different categories of epistemic practice
- 2. Different categories of the corresponding learning outcomes
- 3. Different mechanisms by which engineering knowledge, skills, and experience are used for interdisciplinary learning
- 4. Different barriers perceived and their relationships to the corresponding epistemic practices and learning outcomes
- 5. Different modes of epistemic engagements

### 7.2.1 Categories of epistemic practices

The literature on interdisciplinary practice has specifically emphasised the importance of knowing 'how to learn' from other disciplines (Sutherland Olsen, 2009;p.406), but has yet to identify the relevant practices. The following paragraphs discuss the four categories of epistemic practice identified by this research by comparing and contrasting them with findings from the literature.

#### 1. Consultational Epistemic practice (CEP)

This research conceives the CEP as a set of related actions or activities that engineers perform to gain further understanding on the life science knowledge they encounter. The actions/activities largely involve consultation with people whom the engineers perceive as knowledgeable about the knowledge.

The results show that the CEP is likely to occur in the situation whereby engineers perceive that their knowledge is insufficient for assessing the relevance or usefulness of the life science knowledge suggested by their life science collaborators. This is somewhat different from the knowledge transformation view of knowledge integration (Carlile & Rebentisch, 2003), which seems to overlook the likelihood of such situations. Although the literature acknowledges that the assessment of knowledge relevance tends to be problematic due to both the newness and the specialised nature of knowledge, it proposes that specialists who know about the knowledge should transform the knowledge into different forms before providing it to others in order to facilitate the assessment of relevance. In contrast, this research found that the engineers were seldom provided with knowledge in the forms that they can readily assess for its relevance or usefulness; rather, they tend to encounter knowledge suggestions and practices that are not translated/transformed by their life science counterparts. The difference between this finding and the literature suggests the need to refine the knowledge transformation view of knowledge integration in order to make it applicable for interdisciplinary learning in this sub-class. This refinement should incorporate the situation where knowledge is unlikely to be transformed for use by others from different disciplines. It should

also incorporate the necessity for engineers to engage in the CEP in the specified situation so that the lack of knowledge transformation efforts by specialists from other disciplines can be compensated for. This necessity suggests the need to promote and facilitate students' engagement in the CEP.

This emphasis on the necessity of the CEP in interdisciplinary learning in engineering practice reinforces the prevalence of the 'distributed cognition' concept in engineering practice (Trevelyan, 2013, 2014). The concept signifies that engineering practice involves drawing on the knowledge of other engineering and non-engineering colleagues, relying on their skilled contribution (Trevelyan, 2014), much of it is implicit and unwritten (Trevelyan, 2010). When much of the knowledge contributed by other practitioners is in an implicit and unwritten form, rather than in the form that support engineers' need for assessing relevance, it makes sense for them to take the knowledge into consultation with knowledgeable colleagues. As the understanding of engineering practice as an 'actor network' (B. Williams & Figueiredo, 2013) also found, engineers usually exploit their network of relationships to do their work.

#### 2. Comparative Epistemic Practice (CPEP)

This research conceives the CPEP as the practice of comparing knowledge suggested or practised by others against a set of criteria that are underpinned by engineers' prior knowledge. Actions that constitute this practice include judging the extent to which the knowledge suggestions would satisfy the criteria, and predicting how they would fare if adopted. This finding directly addresses the question of how the assessment of knowledge relevance is actually practised. Furthermore, it highlights that certain engineering knowledge elements are formulated/packaged as evaluation criteria, and are then used for assessing the relevance of knowledge contributed by practitioners from different disciplines. Such a use could hardly be found in the literature except in the study by Gherardi and Nicolini (2002). In their studies on learning about safety by engineers, managers and contractors at a construction site, they found that, unlike the managers and the contractors, the engineers' understand safety as a form of a

check-list. When they encounter the practices and conceptions of safety by others (i.e. practical knowledge on safety), they use their 'check-list' to make comparison, before deciding which practices and conceptions are relevant for maintaining safety at the construction site. The similarity between the findings from at least two studies suggests that the CPEP might be quite common in engineering practice, but are less reported because studies on interdisciplinary practice in engineering are scant. This comparative evaluation is different from the one found by Lattuca *et al.* (2011) in their study of interdisciplinary courses. They highlighted the evaluation of 'logical consistency', but did not specify how prior knowledge is used for the purpose. Therefore, this finding would help advance the idea of using engineering knowledge as a form of criteria for evaluating knowledge through comparison.

#### 3. Translational epistemic practice (TEP)

This research conceives the TEP as a set of related activities taken on the contents and forms of life science knowledge in order to arrive at the corresponding contents and forms that can be used for developing solutions. It is found that during the engineers' consultation with their life science counterparts, they often encounter knowledge elements in the form of qualitative descriptions laden with disciplinary jargons or are embodied in everyday practices of the life science practitioners. Therefore, they often find it necessary to translate them into something quantitative and explicit in order to design and develop solutions. This finding appears to be complementary to that of the knowledge transformation view, which emphasises the representation of knowledge by the knowledge owner for others. The TEP concept is similar to the other concepts in the knowledge management and the organisational learning literature, such as knowledge conversion (Nonaka, 1994). This suggests that the TEP is common in workplace learning practice. In engineering education, a similar practice, known as, knowledge representation (Johri et al., 2013) has been promoted. It is increasingly recognised that the creation and use of knowledge representation is a critical part of engineering practice and education especially in interdisciplinary collaborations (Pande & Chandrasekharan, 2017). The above discussion supports the ongoing effort to develop the ability to engage in activities related to TEP among engineering students.

## 4. Evidential Epistemic Practice (EEP)

EEP refers to a set of related activities taken to gain and show confirmation on the usefulness of the different contents and forms of knowledge to be integrated into the solutions. Engineers and their collaborators often face situations whereby evidence of knowledge usefulness is required to be produced and shown before deciding whether to integrate the knowledge into solutions under development. The prevalence of this practice is congruent with the recent writings on professional practice in knowledge society, where the availability of, and the accessibility to, knowledge are widespread. (Nerland & Jensen, 2012, 2014b), for example, state that two of the necessary practices that have emerged from an extensive distribution of knowledge in today's information society are the practices of testing out the feasibility of knowledge and its relevance, and of questioning the validity of accepted knowledge.

The identification of the four categories of epistemic practices that resonates with the extant literature is theoretically important. As well as advancing the literature on interdisciplinary practice (Nersessian & Newstetter, 2014; Sutherland Olsen, 2009) that has yet to identify learning practices, it informs engineering education that the four epistemic practices are aligned to engineering practice in the workplace. Therefore, they are useful for preparing engineering students for engineering practice.

## 7.2.2 Categories of learning outcomes

The literature on interdisciplinary learning has been speculating learning outcomes but has yet to provide empirical evidence of their relevance. The following paragraphs discuss the four categories of learning outcomes identified by this research by comparing and contrasting them with findings from the extant literature.

#### 1. Knowledge adoption outcome

This research conceives the concept of a knowledge adoption outcome as the attainment of understanding, appreciating, and reusing the relevant knowledge of the life sciences while retaining its original contents and meanings. To the extent that solutions work as expected, the engineers often found it necessary to maintain knowledge in its original form, such as reusing disciplinary jargon in knowledge description and replicating the existing procedural knowledge of the life sciences. Such reuse of knowledge that is already familiar to the life science users helps increase the diffusion of the solutions in the life science domain.

The relevance of the knowledge adoption outcome has been speculated in the interdisciplinary learning literature as noted by Lattuca *et al.* (2004). In addition, it is also commonly found in the extant literature albeit with some differences in the terminologies such as knowledge utilisation by Sussman and Siegal (2003), knowledge re-use by Markus (2001), knowledge replication by Gray and Meister (2004), and knowledge application Liyanage *et al.* (2009).

However, the literature appears to conflate the two different types of knowledge reuse – reusing with and without changing the original knowledge forms and contents. The importance of the knowledge adoption outcome highlights the contingent necessity to be conformant to some of the existing knowledge of the other disciplines, providing that such conformance does not hinder solution development.

#### 2. Knowledge Translation outcome

The knowledge translation outcome encompasses a broad range of achievements that result from developing knowledge through changing original knowledge contents, or/and forms into more useful ones. Engineers gain and use knowledge elements that are distinct from the knowledge of the life sciences from which those elements were derived. This finding appears to support the speculation on the relevance of constructing own understanding of knowledge of other disciplines by interpreting it and by creating new knowledge (Lattuca *et al.*, 2004). In the engineering practice literature, it also resonates with the argument by (Vicenti, 1990) that engineering has a distinct body of knowledge that is different from the natural sciences, and that engineering is not simply the application of knowledge of the natural sciences to problems. This finding highlights that it is important to give a separate but dedicated attention to the two related but distinct outcomes – the knowledge translation outcome and the knowledge adoption outcome. The relevance of the knowledge translation outcome strongly challenges the adequacy of the 'acquire-and-apply' view of learning for characterising interdisciplinary learning in engineering practice. Such a view would have to be revised with a more differentiated view on interdisciplinary learning outcomes found by this research.

#### 3. Knowledge Avoidance outcome

Since the assessment of knowledge relevance is a necessary part of interdisciplinary collaboration, it is not surprising to find that the knowledge avoidance outcome is one of the outcomes of interdisciplinary learning in engineering practice. However, its relevance has not been speculated explicitly by the interdisciplinary learning literature.

In the studied sub-class, the outcome stems mostly from the ambitions of the engineers to develop systems that are simple and easy to be used by the nontechnically-oriented life science users. Frequently also, the engineers find themselves in a difficult situation whereby their life-science collaborators insist on the re-use of existing knowledge related to the life sciences. When the engineers perceive that such re-use would result in suboptimal solutions, they tend to avoid reusing it. Most of the time, the knowledge is embedded in the existing tools, processes, or procedures that the life science users are already familiar with, but are hindrances to the effectiveness and efficiency of their practices. As a result, achieving the knowledge avoidance outcome usually entails significant efforts by the engineers to challenge the status quo.

Although the knowledge avoidance outcome seems inevitable in interdisciplinary collaboration, its necessity tends to be obscured in the literature. For example, there appears to be only an implicit indication of its importance in the interdisciplinary practice of engineering scientists in Biomedical Engineering (Nersessian & Newstetter, 2014). They found that "a major learning challenge…is to develop a selective, integrated understandings" (p. 720) in terms of relevance to goals and problems.

#### 4. Knowledge Addition

This research conceives the concept of knowledge addition outcome as the ability to contribute knowledge that is new to the collaborators of other disciplines who then adopt it as their domain knowledge. It involves the diffusion of knowledge from engineering discipline to the life science practice domain.

It was found that the engineers acknowledge the relevance and usefulness of the knowledge contributed by their life-science counterparts; however, they also perceive that unless the knowledge is complemented by other knowledge elements, its usage would be insufficient for solving the problems at hand. Although the engineers have little difficulty in identifying knowledge to contribute, they have much difficulty in arguing for the acceptance of it by their life science counterparts who lack familiarity with the knowledge. Hence, a combination of different epistemic practices is necessary for achieving the outcome.

This outcome has not been speculated by the interdisciplinary learning literature. However, it is somewhat related to the concept of knowledge combination, which can be found in the literature that concerns with combining knowledge that are dispersed across locations (Buckley & Carter, 2004; March, 1991; Taylor & Greve, 2006). However, unlike the knowledge addition outcome, the knowledge combination concept does not necessarily involve the diffusion of knowledge from one discipline to another.

The above findings provide empirical support to some of the speculated learning outcomes and identify some new ones. Together with the findings on epistemic practices, they usefully provide answers to the first research question on "how engineers practise their interdisciplinary learning in terms of their engagement in epistemic practices, and their achievements of learning outcomes?".

The most revealing insight from the above discussion is that the learning of the engineers does not conform to the conventional 'acquisition-and-transference' view of learning. Rather, the identification of the four epistemic practices and the variation in the learning outcomes supports the socio-material view of learning that emphasises what learners do with the knowledge they encounter. In addition, the findings help refine the understanding of the knowledge integration process for the sub-class by incorporating the contingent need for the CEP. Another finding that is related to the Comparative Epistemic Practice helps advance an emerging but currently obscured idea of using engineering knowledge as criteria for evaluating knowledge suggestions. Finally, the other findings reinforce the importance of engaging in producing knowledge representations and in testing out knowledge suggestions.

The subsequent sub-sections discuss findings that provide explanations for the identified epistemic practices and learning outcomes.

# 7.2.3 How engineering knowledge, skills and experiences are capitalised for interdisciplinary learning

The literature on interdisciplinary learning encourages researchers to study the 'hypothesised routes to learning' and challenges to 'probe the precise mechanisms through which interdisciplinary study has such widespread effects" (Lattuca *et al.*, 2004;p.42). The findings reveal six mechanisms that could explain the engineers' ability to sustain learning through the identified practices towards achieving the learning

outcomes. The ensuing paragraphs discuss these mechanisms and the extent to which they are covered by the existing literature.

## 1. Relating

'Relating' has been identified as the mechanism by which the analogous perception of knowledge of the life sciences leads to the knowledge adoption outcome, as shown in Figure 6.1. It explains how the engineers relate their existing engineering knowledge as an analogy to new knowledge, thereby enabling them to adopt and retain it. The identification of this mechanism resonates with research on the structure of memory, which establishes that relating unfamiliar information to that which is familiar facilitates the acquisition and retention of knowledge (Stepich & Newby, 1988). It is also similar to the findings from research on the use of analogies in relating prior knowledge that is organised and stored in the learner's memory for the acquisition of new knowledge (Ausubel, 1960).

The finding from this research thus provides empirical supports for the hypothetical explanation by Lattuca *et al.* (2004), in section 2.3.2, which proposes that by organising disciplinary knowledge into mental models known as a 'schemas', it could then be used to learn knowledge from different disciplines. In addition to this empirical support, the finding also highlights the need to refine our understanding of how engineering knowledge is actually used in interdisciplinary practice. In contrast to the naïve but prevailing view of 'applying' knowledge that is created or learnt in one domain to be used in another domain, the finding helps refine it with the more accurate concept of 'relating'. The latter highlights the need to discern the similarities and differences between the existing knowledge used as analogy and the new knowledge. While the recognition of the similarities facilitate and motivates the engineers to start engaging with the new knowledge, the recognition of the difference helps them to develop a deeper understanding through refining their existing 'schema' and restructuring their existing mental model to accommodate the differences. This

depth in engagement with the knowledge constitutes deep learning that makes knowledge retention more likely.

### 2. Representing

'Representing' has been identified as the mechanism by which the perspectival mode of epistemic engagement leads to the engagement in the TEP, as shown in Figure 6.1. The finding suggests that engineers use their knowledge, skills and experiences in creating and manipulating representations in learning life science knowledge.

The identification of the representing mechanism is congruent with the argument that representations are "unique and understudied aspects of learning with important consequences for engineering learning" (Johri *et al.*, 2013;p.2). The use of representation can be effective in facilitating collaborative design because successful representations present and organise recognitions so that they are recognisable across multiple disciplines (Juhl & Lindegaard, 2013).

The identification of the 'representing' mechanism implies the inadequacy of the notion of 'transferring' knowledge in explaining why engineers are able to learn knowledge from other disciplines. 'Representing' highlights that learning from other disciplines is not only about transferring knowledge without changing its forms and contents.

### 3. Rationalising

'Rationalising' emerges in this research as the mechanism by which the justificational mode of epistemic engagement leads to the engagement in the EEP, as shown in Figure 6.1. The finding suggests that engineers use their skills and experience in rational thinking and in formulating logical arguments for making and influencing decisions.

This finding encourages us to refine the view advanced by the socio-material perspective on learning that knowledge suggestions need to be tested and assessed for their relevance and usefulness before they can be used in a new context (Nerland & Jensen, 2012). It suggests that a prior mechanism of 'rationalising' is necessary in prioritising and reducing the vast amount of testing to be done especially in the increasing availability and accessibility of knowledge.

#### 4. Experimenting

'Experimenting' is the mechanism by which the implicational mode of epistemic engagement leads to the engagement in EEP, as shown in Figure 6.1. In this research, it was found that experimenting is the mechanism by which engineers use their prior knowledge in order to conduct more efficient investigations. They use prior knowledge to make informed guesses, rather than to make full investigative experimentation based on pure 'trial-and-error'. In other words, engineering experimentation is a 'guided experimentation' rather than a blind one.

### 5. Envisioning

The 'envisioning' mechanism explains how difficulties in contributing knowledge are overcome. It is necessary for the engineers' successful engagement in evidential epistemic practices and achievement of knowledge addition. Since the knowledge addition outcome has not been speculated, the identification of this mechanism is unexpected although the outcome is somewhat similar to the one propose by the knowledge combination literature.

#### 6. Satisficing

The 'satisficing' mechanism explains how the learning outcomes that are based on evidence could be accomplished at a level of depth and breadth of interdisciplinary learning that is sufficient for producing solutions that satisfies the expectations of the users. The identification of this mechanism suggests that the depth and breadth of knowledge of other disciplines that is integrated by engineers in the solutions to problems is likely to be determined by satisfactory acceptance of the solutions by the intended users.

# 7.2.4 Barriers and their relationships with epistemic practices and outcomes

The findings identified four barriers as the reasons for the deployment of different epistemic practices. These are situational perceptions that make interdisciplinary learning difficult.

- 1. Communication barrier
- 2. Contradictory barrier
- 3. Contributory barrier
- 4. Implicational barrier

The following paragraphs discuss the four types of barriers by comparing and contrasting them to those found in the literature.

1. Communication barriers

It was found that the perception of communication barriers is likely to cause engagements in the TEP. This causal relationship resonates with the one proposed by the literature on knowledge integration. The literature relates two types of barrier syntactic and semantic barriers – to a number of translational practices, such as representing knowledge in different forms (Carlile, 2004). Similar to the literature, this research also found that this relationship is likely to lead to the achievement of the knowledge translation outcome. In addition to reinforcing the relationship that has been established by the extant literature, this research also specifies that the perception of communication barriers is likely to relate to another category of outcome termed as the knowledge avoidance outcome. This means that overcoming communications barriers through engagement in the TEP also contributes to the identification of knowledge elements that can hinder the successful development of solutions. This is especially the case when engineers represent the life science knowledge for eliciting the implicit form of knowledge or for deriving the corresponding quantitative form. The removal of the communication barrier thus allows engineers and their life science counterparts to jointly evaluate, or test, the usefulness of the knowledge. This facilitates the joint agreement to avoid knowledge that is not evidently useful for solving problems.

2. Contradictory barriers

It was found that contradictory barriers relate causally to engagements in EEP. Further, this research also found that this relationship is likely to lead either to the knowledge adoption outcome or to the knowledge avoidance outcome. The contradictory barriers to learning knowledge arise when there is no perceived communication barrier to communicating and understanding the knowledge but the knowledge itself is perceived as discordant by the engineers since the actual practices of their life science counterparts appear to contradict the knowledge they espouse. This causes the engineers to either hesitate or refuse to adopt the knowledge.

The perception of contradictory barriers is not uncommon in professional practice in general and in engineering practice in particular. For example, the engineer practice literature "established that engineering work is complex, ambiguous, and full of contradictions" (Johri, 2014;p.121).

### 3. Contributory barriers

It was found that contributory barriers relate causally to engagements in EEP. This research also found that this relationship is likely to lead to the knowledge addition

outcome. Such barriers are likely to arise due to the difficulty of the life science counterparts in foreseeing the results of complementing their knowledge with the knowledge proposed by the engineers. Although the knowledge itself may be understood, the value of accepting the knowledge contribution may not be appreciated easily without going through tests that generate evidence of the expected results. This specification of the relationship between contributory barriers, the EEP, and the knowledge addition outcomes appears to be absent from the interdisciplinary learning literature.

#### 4. Implicational barriers

It was found that perceived difficulties that constitute implicational barriers relate causally to engagements in the EEP. This research also found that this relationship is likely to lead either to the knowledge adoption outcome or to the knowledge avoidance outcome. Such barriers arise during the CEP due to the uncertainty surrounding the implications of the knowledge suggestion for the solutions to be developed or under development. Although the life science collaborators are able to communicate the knowledge well, they often do not know enough about the solutions that the engineers seek to develop. Therefore, they often do not know the possible implications of the knowledge is impeded by the uncertainty about the possible implications (i.e. the implicational barrier). As a result, engineers often resort to engage in the EEP in order to learn specifically about the implications. Depending on the evidence, the overcoming of the implicational barrier through engagement in the EEP is likely to cause either the adoption of knowledge, if it is shown to affect the development of solutions, or the avoidance of it, if the evidence shows otherwise.

Many of the above barriers have not been identified by the interdisciplinary engineering education literature (Richter & Paretti, 2009) and causal relations have not been specified. In specifying the causal relationships discussed above, it was also found that they are contingent upon the different modes of epistemic engagements. When faced with the above barriers, engagements in the corresponding epistemic practices become more likely when engineers orientate into the specific modes of epistemic engagement.

## 7.2.5 Modes of epistemic engagements

There are four modes of epistemic engagement that relate in specific ways to the four barriers in that the modes are more likely to enable the engineers to activate the relevant mechanisms.

1. Perspectival mode of epistemic engagement

The engagement in this mode is likely to enable engineers overcome, rather than succumb to, communication barriers and subsequently engage in the TEP, as shown by the theoretical framework in Figure 6.1. In this mode, the engineers tend to engage with knowledge from the life sciences by viewing it from multiple perspectives, such as from the life science users' perspective as well as from an engineering perspective.

These perspectives help engineers use the 'representing' mechanism, which harnesses their knowledge and skills in producing representations. Their orientation into this mode enables them to produce knowledge representations that address the needs of others for participating in the translation process. Since the participation of others is also necessary to the development and the adoption of the solutions, the orientation into the perspectival mode could increase the propensity of achieving the desired outcomes.

2. Justificational mode of epistemic engagement

This mode is likely to enable engineers to overcome, rather than to succumb to, contradictory barriers and subsequently engage in the EEP, as shown by the

theoretical framework in Figure 6.1. In this mode, the engineers tend to tolerate ambiguity in knowledge claims or contradictions in practice, and see them as opportunities to interrogate the different justifications to those claims and practices. Coupled with the "rationalising' mechanism, which capitalises on their rational thinking, their orientation into this mode enables them to identify the kinds of tests and evidence that would be required for interrogating and testing the different justifications. This facilitates a collaborative rationalisation on what should be done to the knowledge. As a result, it guides the engineers' engagement in the EEP that could lead to the appropriate outcomes.

3. Complementary mode of epistemic engagement.

This mode is likely to enable engineers to overcome, rather than to succumb to, contributory barriers and subsequently engage in the EEP, as shown by the theoretical framework in Figure 6.1. In this mode, the engineers tend to find ways in which they could position their prior knowledge as complementary to the life science knowledge suggested to them. Coupled with the 'envisioning' mechanism, which capitalises on their experiences with similar projects elsewhere, they formulate a vision of the realisation of the benefits of the complementary combination of knowledge. The responses of their life science counterparts can then be used to guide the choice of tests and evidences on the envisioned benefits of the knowledge combination. As a result, it guides the engineers' engagement in the EEP that leads to the knowledge addition outcome.

4. Implicational mode of epistemic engagement

This mode is likely to enable engineers to overcome, rather than to succumb to, implicational barriers and subsequently engage in the EEP, as shown by the theoretical framework in Figure 6.1. In this mode, the engineers tend to direct their investigation towards determining whether the knowledge they encounter has implications for the solutions under development. Coupled with the experimenting mechanism, which capitalises on their skills in engineering experimentation and knowledge about the solution under development, they are able to design suitable tests of the possible impact of the knowledge on the solutions. As a result, it guides the engineers' engagement in the EEP that could inform the appropriate outcomes.

The findings discussed in the previous three sub-sections answer the second research question by providing specific explanations on "why engineers engage in different epistemic practices, and achieve different learning outcomes?" The answers indicate that the identified epistemic practices are necessarily triggered by the different perceptions of barriers. However, the orientations into the different modes of epistemic engagement are necessary to activate the different mechanisms that enable their engagements in those practices.

Although the above discussion clarifies how the findings have usefully addressed the two research questions in a way that contributes to the current literature, there appear to be some limitations in their theoretical value.

# 7.3 Methodological discussion

The methodological discussion focuses on the extent to which the analytical methods have jointly or individually contributed to the quality of the findings.

## 7.3.1 Methodological findings

There are three main issues pertaining to the application of the methods. These are discussed below.

1) Credibility of the methodology

The application of the methods was intended to ensure credibility in the findings that identify and explain the specific aspects of the studied phenomenon. This research had anticipated some limitations in the accessibility, observability, and measurability of the different aspects that it sought to identify and explain. Events that occurred in the past - such as past engagement in epistemic practices - are no longer observable. Similarly, it is difficult to access and identify situational perceptions, such as barriers that tend to arise in interdisciplinary interaction. Since data collection relied heavily on retrospective accounts of, and subjective interpretations by, different people including the researcher and his informants, credible production of knowledge requires evaluation in terms of how closely the identifications and explanations correspond to what actually happened.

It is found the methodological approach had successfully overcome the limitations in accessibility, observability and measurability of the important aspects in a credible manner. It dictates the use of additional 'data', in the form of descriptive and explanatory inferences. These are then analysed for congruence and plausibility. For example, the researcher had introduced perceptual variables that were not mentioned by his informants for explaining their engagement in epistemic practices. This has led to the identification of the four barriers that explain why epistemic practices emerge in interdisciplinary learning.

It was found however that by itself, the introduction of additional inference did not increase the credibility of the findings. Rather, credibility is enhanced also through a combination of methods that adjudicate among competing inferences. The research is able to achieve a reasonable degree of credibility in the descriptions and explanations because the descriptive and explanatory inferences had been challenged by their rival inferences, and had survived the various tests provided by the comparative method, the congruence method, and the causal process tracing test. Moreover, both the process of introducing and adjudicating among inferences are done in transparent manner using both the interview and archived types of data. Consequently, the approach relies more on evidence-based arguments and less on subjective persuasion.

These methodological practices also raise the standard of conducting case study research, which has been criticised as being too subjective and relying more on persuasiveness of arguments, rather than on evidence and systematic tests (Bennett, 2010; Flyvbjerg, 2006). Thus, the knowledge produced and the methodology has a good degree of credibility for the engineering education community to consider.

## 2) Transferability of the findings

The methods are applied to study the interdisciplinary learning phenomenon in the workplace settings, but the research has sought to transfer the findings to the educational settings. This raises the issue of the transferability of the findings due to the substantial differences in the contexts and situations.

It is found that the grounding of the methods in the critical realist philosophical position has been advantageous to the transferability of the findings to the educational settings. Critical realism philosophy conceptualises about a phenomenon by specifying situations that are likely to have caused events of interest. It also emphasises identifying interactions that are causal in the researched settings. Further, it theorises that similar events are likely to occur in other settings providing that the specified situations and interactions are also present (i.e. a contingent rather than a deterministic generalisation). Therefore, it has enabled this research to inform engineering education that the specified events are likely to occur also in the educational settings providing that the situations (e.g. perceptions of barriers) and interactions (i.e. mode of epistemic engagement) are also present. Moreover, it clarifies that the actual occurrences of similar events in other settings are never definite since other situations might be present to counter them. Therefore, the results should be transferred for predicting events in other settings.

This kind of contingent transferability is likely to be valuable to students and educators. Instead of being prescriptive, it empowers students to perform analysis of their situations in interdisciplinary interactions, and make own judgment on the way they should proceed with the subsequent interactions. Similarly, educators can use the theory to support students with suitable interventions strategies for understanding the situations and exercising judgments on the appropriate choice of epistemic practices. The findings are transferable despite the difference in settings mainly because the methods used, in particular the ANT-analytical framework, facilitates the identification of only the causally relevant situations and interactions. Otherwise, the researcher could have resorted to the usual practice of 'thick' reporting of all the situations in each case, and would be disappointed in transferring the results due to the many substantial differences between the workplace and the educational settings.

3) Dependability of the methods

Transparency in applying a set of established methods allows others to repeat the research, either with the same or with different methods. This may lead to findings that may or may not agree with the findings of this research.

If the findings were similar, then they would reinforce each other. Otherwise, the methodology dictates that competing findings should be subjected to arbitration. In this sense, the methodology is dependable since it provides a platform on which different researchers can share their findings and jointly evaluate them to improve their collective understandings of the phenomenon. The tests used to adjudicate among competing inferences would allow researchers to differentiate between different types of evidence according to the different implications they might have on the plausibility of the inferences and their corresponding rivals.

## 7.3.2 Methodological contributions

The main methodological contribution made by this research is the complementary combination of methods for analysing the research data. It contributes to the critical realism philosophy since the methodological procedure developed and implemented by this research addresses the concern of the lack of clear guidance on how to apply the critical realism philosophy to actual research methodologies (Fletcher, 2017; Wynn & Williams, 2012). Specifically, it adds value to the current critical realist methodology – which until now is still lacking in rigorous methods to incorporate, and adjudicate among, competing inferences – by showing how critical realist research can use

systematic test procedures offered by scholars in international relations research. The combination of methods also responds to the call for "greater attention to means of combining alternative methodological approaches" (Bennett & Elman, 2006;p.456). Additionally, since the methodology used by this research enables the transfer of findings from the practice settings to the educational settings despite the apparent differences in contexts, it also contributes to the emerging translational approach to transforming engineering education (Nersessian & Newstetter, 2014).

## 7.3.3 Methodological limitations

Despite the complementary combination seeking to compensate for the weakness of the individual methods, there are some limitations in the methodology.

The implementation of the methodological procedure results in a lengthy analysis mainly due to choice of combining the seven methods in series. The coding analysis and the ANT-analytical framework could have been applied in parallel in order to shorten the process of analysis. Coupled with the intensity in analysing each cases, the lengthy procedure limits the number of cases that could be studied in depth within the remit of the available resources. Furthermore, the methodological approach of selecting cases that contain the least-likely and most-likely practices for each of the propositions have reduced the number of cases of interdisciplinary collaboration (i.e. three cases) on which the proposed theory are based. Although the number of cases analysed appear to be optimal for generating many useful findings that cover wide-ranging aspects of interdisciplinary learning, the research could not claim that it has exhaustively identified all the relevant aspects of interdisciplinary learning for the sub-class.

The application of the cross-case comparison method for refining and evolving the theoretical framework only analyses cases of interdisciplinary collaborations that result in successful development and diffusion of the solutions. Cases that are less successful, or so-called 'negative cases', are not analysed. These cases are useful for increasing our confidence in the proposed theory; if the variables that describe and explain the successful cases are absent from the 'negative cases', then our confidence in the proposed description and explanation could be increased. However, the other methods, such as the congruence and the CPT, demand documentary evidence that are more

difficult to locate in the less successful cases. Many of these methods are borrowed from international relations research, where the identifications of different types of comparative cases are eased by the availability of countries data, unlike cases of interdisciplinary learning, wherein the availability of data to support such identification is uncertain.

Finally yet importantly, the rigour in introducing and adjudicating among rival explanations is as good as the number of alternative explanations that were supplied to the method. Consistent with the intention to inform interdisciplinary learning in engineering education, rival explanations were sourced mainly from the learning literature. The inclusion of alternative explanations sourced from other perspectives, such as from a team-working perspective, could increase the rigour in the analysis.

# 7.4 Summary of the key insights of the discussion

Based on the synthesis of the theoretical and methodological findings, this discussion chapter concludes by summarising the key insights.

The first set of insights arises from the way that interdisciplinary learning is described in terms of the four epistemic practices and the corresponding four learning outcomes. The establishment of the necessity of the CEP reinforces the prevalence of the notion of 'distributed cognition' whereby engineers learn from knowledgeable others. On the other hand, it implicates the refinement of the knowledge integration view that proposes engineers can readily assess the relevance of new knowledge. The refinement needs to incorporate the situation whereby the life science counterparts do not provide knowledge in the forms and contents that enable engineers to proceed with the assessment of their relevance to the problems at hand. In addition, the establishment of the necessity of the comparative epistemic practice advances the currently obscure idea that engineering knowledge can be used as a form of criteria for evaluating the usefulness of knowledge of other disciplines. Further, since the epistemic practices encompass more than acquiring and transferring of existing knowledge of the other non-engineering discipline and the learning outcomes encompass more than knowledge acquisition, it is clear that the 'acquisition-andtransference' view of learning is inadequate to describe the aspects of interdisciplinary learning in engineering practice. The socio-material view of learning has been established as a view that is closer to what is currently practised in the sub-class.

The second set of insights is gained from the identification of the mechanisms that explain why engineers were able to engage in those practices despite facing learning difficulties. The establishment of the 'relating' mechanism, which relates engineering knowledge as an analogy to corresponding life science knowledge is more representative than the notion of 'applying' engineering knowledge from one domain to another. As an explanation of how new knowledge is gained and retained, the 'relating' mechanism is more accurate than 'applying'. 'Relating' signifies deeper learning as it also enables the recognition of differences between the analogy and the knowledge to be learnt, thereby leading to the restructuring of existing mental model. In 'applying', such deep learning and restructuring is less likely to happen due to the limitation of the superficial recognition that the existing and the new knowledge is similar. In addition, the 'representing' mechanism highlights the inadequacy of the 'transferring' mechanism, and the 'rationalising' and 'experimenting' mechanisms refine the socio-material idea of testing knowledge for its usefulness when opportunities for prioritising which knowledge to be tested are present and can be facilitated by existing knowledge. Finally, the 'envisioning' mechanism explains how difficulties in contributing knowledge are overcome to achieve knowledge addition.

The third set of insights encompass all the newly identified barriers and modes of epistemic engagements that add on to the list in the literature but also provide more refined and contingent explanation for the epistemic practices and learning outcomes.

Combined with the methodological findings on credibility, transferability, and dependability, the above insights enable the research to draw conclusion on the implications for research and practise in interdisciplinary learning specifically and in engineering education more generally.

# **Chapter 8 Conclusion**

This chapter concludes the thesis with the assessment of the significance of the findings. It highlights their contributions to theory and draws their implications for educational practices. In addition, it also explains the limitations of the findings. This chapter ends with some recommendations for future research.

This conclusion chapter is thus organised into four main sections:

Section 8.1: Contributions to theory – highlights the theoretical significance of the findings

Section 8.2: Implications for practice – draws the implications of the theoretical contributions for educational practices in higher education

Section 8.3: Limitations of the findings – identifies and explains the limitations of the findings

Section 8.4: Recommendations for future research – suggests areas that could be investigated further

# 8.1 Contributions to theory

The contribution of this research to theory is determined by assessing the significance of the two different sets of findings: the descriptive findings and the explanatory findings.

The descriptive findings refer to the set of four categories of epistemic practices and the set of four categories of learning outcomes. On the other hand, the explanatory findings refer to the situational perceptual variables, modes of epistemic engagement, mechanisms, and the causal relationships embodied in the different pathways to learning outcomes.

This theoretical contribution section is organised into four sub-sections:

- Subsection 8.1.1 assesses the significance of the descriptive findings involving the four categories of epistemic practices. The assessment will show how they contribute towards the development of a practice-based theory of interdisciplinary learning.
- 2) Subsection 8.1.2 evaluates the significance of the explanatory findings involving the situational perceptual variables and modes of epistemic engagements. The evaluation will show how they contribute towards the development of a contingency theory of interdisciplinary learning.
- 3) Section 8.1.3 assesses the significance of the descriptive findings involving the four categories of learning outcomes. The assessment will show how they contribute towards the establishment of the applicability of the notion of 'selective, integrated understanding' for describing the outcomes of interdisciplinary learning in engineering practice.
- 4) Section 8.1.4 evaluates the significance of the explanatory findings involving the mechanisms and the different learning pathways. The evaluation will show how they contribute towards the development of a typological theory of interdisciplinary learning.

# 8.1.1 Theoretical significance of the four conceptual categories of epistemic practice

The understanding of interdisciplinary learning has so far been informed mostly by the process-based theory of interdisciplinary learning proposed by interdisciplinary studies scholars. The theory offers descriptions of the steps that should be undertaken by interdisciplinary learners when they study complex problems, such as the environmental problem of acid rain. In the first step, the interdisciplinary learners are exposed to a complex problem. Then, the learners are expected to draw and integrate insights from multiple disciplines. Finally, the theory suggests that by integrating those insights the learners could attain a comprehensive understanding of the problem and propose how to solve it. In essence, the learning process relies heavily on the ability of the learners to acquire multiple insights for understanding and solving the problem.

This process-based theory has been used to inform the use of an interdisciplinary approach both for preparing engineering graduates for interdisciplinary practice and for promoting intellectual development among undergraduates. However, the extent of its usefulness has been found to be limited because it has not been sufficiently informative. Engineering education researchers and practitioners would like to be informed about how learning in interdisciplinary problem-solving is intertwined with problem-solving practices that characterise engineering work in classrooms and workplaces. It is not clear how those aspects of engineering practices found by researchers, such as 'technical coordination', 'creating', 'checking', 'representation', and 'professional judgement' (Trevelyan, 2009; B. Williams & Figueiredo, 2013) are useful for interdisciplinary learning since these engineering practices do not rely solely on the ability to acquire multiple insights and knowledge from others. In addition, proponents of interdisciplinary learning for intellectual development would like to know how to overcome the risk of leaving behind students who are less intellectually developed in their view of knowledge. Exposure to multiple and sometimes contradictory perspectives in interdisciplinary activities can be problematic for such students (Ivanitskaya et al., 2002), especially for those who view learning as acquiring and recalling factual knowledge that are provided unambiguously by instructors.

Intellectual development of university students and their views of knowledge have been extensively studied and conceptualised. One of the most frequently cited conceptions is Perry's scheme of intellectual development of university students (Perry, 1999). It proposes nine positions, which are often categorised into four stages of development (Hofer & Pintrich, 1997; Perry, 1981):

Stage 1: Dualism

At the earlier position 1 (Basic Duality) and position 2 (Multiplicity Pre-legitimate), students mostly receive knowledge provided by instructors without questioning its truth. In dealing with multiple knowledge provided by others, they tend to perceive it in dualistic term of either true or false. They tend to believe that for any question, there has to be one knowledge as the correct answer, and it is the one provided by authorities, such as their instructors. Their learning revolves around acquiring and recalling knowledge they perceived as unambiguous facts. Therefore, 'dualistic learners' who seek to learn by acquiring factual disciplinary knowledge would find it difficult to acquire and integrate knowledge whose relevance to problems appears contested, uncertain and ambiguous.

#### Stage 2: Multiplicity

At position 3 (Multiplicity subordinate) students begin to recognise that in some knowledge areas there are multiple and conflicting opinions even among authorities, but nevertheless believe that authorities can arrive at the right answer. However, when they realise that in some areas even authorities could not agree with each other, they are inclined to view that all opinions are equally valid and everyone is entitled to their own opinions (Position 4: Multiplicity correlate or Relativism subordinate). At this stage, however, some students may retreat to stage 1. 'Retreating' refers to returning to dualist stage due to the inability to cope with the perceived uncertainty and ambiguity (Perry, 1981;pp.90-1).

#### Stage 3: Contextual Relativism

In Position 5 (Relativism correlate, competing or diffuse), students recognise that there are multiple contexts in which knowledge can be applicable. They realise, however, that knowledge tend to be contextual in that some appear to be relatively better than others depending on the context. Hence, they realise the need to actively construct contextual meanings and implications of the different knowledge. In Position 6 (Commitment foreseen), they understand that in many contexts, knowledge tend to be relative, contingent and contextual; therefore they began to commit to making their own choices and affirming their positions. At this stage, however, some students may escape from making such commitment. 'Escaping' refers to avoidance in dealing with the complexity

and uncertainty of the relativist stage by not taking positions of their own on certain issues, and thus avoiding commitment (Perry, 1981;p.90-1).

### Stage 4: Commitment within relativism

In Position 7(Initial commitment), students began focusing on engaging with the relativity of knowledge as they are aware of their responsibilities, personal identities and values. In position 8 (Orientations in implications of commitment) they realise that there are implications of making those commitments, and therefore develop their commitments further in position 9 (Developing Commitment(s)).

Perry (1981) also proposed that changes in students' views on the nature of knowledge would be accompanied by changes in their ways of learning. However, such changes are not definite as Perry had disclosed some difficulties in the form of 'temporizing', 'retreating' and 'escaping', which can result in their "deflection from growth" (Perry, 1981;p.90).

'Temporizing' refers to hesitating and postponing their progression to the subsequent stage, often expressing "uneasiness about a failure of responsibility with which they felt helpless to cope". 'Retreating' refers to returning to dualist stage due to the inability to cope with the perceived uncertainty in the relativist stage. 'Escaping' refers to avoiding dealing with the complexity and uncertainty of the relativist stage by not taking a position of their own on the issues, and thus avoiding commitment (Perry, 1981;p.90-1). The process-based theory of interdisciplinary learning does not suggest knowledge practices, or a set of actions, for overcoming these difficulties.

On the other hand, the descriptive findings provide useful suggestions on knowledge practices. These practices have been shown to relate closely to several aspects of engineering practices. Thus, they could usefully inform engineering education. Additionally, these practices have been shown to help overcome interdisciplinary learning barriers. Thus, they could usefully inform how students can sustain their progress in intellectual development during interdisciplinary learning.

The conceptualisation of the four epistemic practices involves showing how several aspects of engineering practice are related to interdisciplinary learning. Specifically,

- 1) The identification of the Consultational Epistemic Practice offers a theoretical description that shows how learning through this knowledge practice is intertwined with one salient aspect of engineering problem-solving called 'distributed cognition', whereby engineers rely on their more knowledgeable others. In the context of interdisciplinary learning, this involves taking the knowledge from other disciplines into consultation with more knowledgeable others.
- 2) The identification of the Translational Epistemic Practice offers a theoretical description that shows how learning through this knowledge practice is knitted together with two germane aspects of engineering problem-solving the use of 'representation' (Johri *et al.*, 2013) and the practice of 'creating' (B. Williams & Figueiredo, 2013). In the context of interdisciplinary learning, this involves translating different forms of knowledge representations and creating prototypes that are used to facilitate the evolvement of requirements and specifications toward an accepted solution.
- 3) The identification of the Comparative Epistemic Practice offers a theoretical description that shows how learning through this knowledge practice is closely linked to one aspect of engineering practice that is 'checking' (B. Williams & Figueiredo, 2013), that is using a checklist to make various kinds of assessment. Of particular importance for interdisciplinary learning is checking different knowledge suggestions in order to assess their relevance and usefulness to problems. In addition, this practice has been used to make comparison between new knowledge suggested by other disciplines and prior knowledge from engineering.
- 4) The identification of the Evidential Epistemic Practice offers a theoretical description that shows how learning through this knowledge practice is intertwined with aspects of engineering problem solving that involves testing

and validation. Of particular importance to interdisciplinary learning is validating the relevance/usefulness of knowledge of other disciplines to the development of solutions by testing whether the integration of the knowledge would result in a solution that works according to an agreed specification.

Thus, it can be claimed that the findings contribute significantly towards a practicebased theory of interdisciplinary learning in engineering practice. It helps contextualise the general process-based theory of interdisciplinary learning offered by interdisciplinary studies to the context of engineering education and to the context of intellectual development.

Such a practice-based theory could have profound implications for educational practice and for sustaining the intellectual development of university students, which are explored more fully in section 8.2.1.

An important consequence of relating the findings to a practice-based theory is the understanding that practices are always emergent, that is 'they change in the light of circumstances' (Rooney *et al.*, 2012;p.5). Therefore, the explanations for the emergences of the four epistemic practices can be theoretically significant.

# 8.1.2 Theoretical significance of the explanations for the emergence of the four epistemic practices

The explanations for the emergence of the four epistemic practices include two sets of findings: 1) Situational perceptual variables, and 2) Modes of epistemic engagement. Together, they also explain how an initial engagement in one knowledge practice could lead to subsequent changes to other knowledge practices. In addition, they show how practices are contingent on the prior variables specified by the findings.

Thus, the descriptive and explanatory findings that include the four conceptual categories of epistemic practice, the seven situational perceptual variables, and the five modes of epistemic engagement together contribute towards a contingency theory of interdisciplinary learning through epistemic practice. This contingency theory establishes that, and explains why, learning practices in interdisciplinary settings are emergent and contingent. They always change according to the changes in learners' perception of the situations. And, these changes are contingent on learners' changes in modes of epistemic engagement. The contribution to this contingency theory could have a profound implication for educational practice, which is explored in section 8.2.1.

# 8.1.3 Theoretical significance of the four conceptual categories of learning outcomes

The process-based theory of interdisciplinary learning advances an understanding of learning outcomes in terms of the notion of 'comprehensive, integrated understanding'. However, a recent investigation of interdisciplinary engineering practice in a biomedical research lab found instead that "a major learning challenge...is to develop selective, integrated understandings...that are relevant to goals and problems" (Nersessian & Newstetter, 2014). A major gap in this alternative understanding of learning outcome is that the constituents learning outcomes of the notion of 'selective, integrated understanding' have not been specified. The identification of the four learning outcomes thus usefully provides a theoretical elaboration of the notion in terms of its constituent learning outcomes. Specifically,

- The identification of the Knowledge Adoption Outcome establishes that one important aspect of 'selective, integrated understanding' involves acquisitionand-transference of knowledge of other disciplines without changing its original content or form.
- 2) The identification of the Knowledge Translation Outcome offers a more nuanced conception of 'selective, integrated understanding' in that that some knowledge that underpins this integrated understanding are not necessarily similar in their contents and forms to the knowledge from which they are derived.

- 3) The identification of the Knowledge Avoidance Outcome provides the most crucial differentiator between the notion of 'selective, integrated understanding' and the notion of 'comprehensive, integrated understanding'.
- 4) The identification of the Knowledge Addition Outcome offers a more realistic conception that all the knowledge elements and insights that underpinned an integrated understanding need to be complementary, rather than contradictory or redundant, to each other.

Thus, it can be claimed that the findings provide a significant theoretical elaboration to the emerging notion of 'selective, integrated understanding'. They offer more meaningful and nuanced theoretical descriptions of knowledge integration within interdisciplinary engineering practice. This could have a profound implication for educational practice, which is explored in section 8.2.2.

# 8.1.4 Theoretical significance of the explanations for the achievements of the four learning outcomes

The explanations for the achievements of the four learning outcomes highlight the dependencies of the learning outcomes on the various mechanisms and types of learning. There are two sets of findings that provide theoretical significance: 1) the mechanisms by which engineering knowledge, skills and experiences are used for interdisciplinary learning, and 2) the different learning pathways that link the engagement in learning practices to the achievement of outcomes. Together they 1) delineate the different types of learning that can occur and 2) explain why interdisciplinary learning exhibit multifinality and equifinality in arriving at the learning outcomes.

Thus, they contribute towards a typological theory of interdisciplinary learning in engineering practice, a theory that specifies how outcomes could be achieved by going through various ways of learning in interdisciplinary engineering workplace. This could have a profound implication for educational practice, which is explored in section 8.2.2.

By integrating all the descriptive and explanatory findings related to practices and outcomes in one theoretical framework, this research provides a significant contribution

towards an integrative theory of interdisciplinary learning in engineering practice. Such a theory both describes and explains a complex integration of learning practices and learning outcomes in interdisciplinary engineering practice.

The next section explores the implications of these theoretical contributions to educational practice.

# 8.2 Implications for educational practices

This section draws practical implications from the theoretical contributions in order to inform educational practices in interdisciplinary approach to higher education learning. It considers the implications both for preparing engineering graduates for interdisciplinary engineering practice and for promoting students' progress in their intellectual development. For engineering education, the implications centre on 1) how to inform the alignment of students learning practices to those practices that characterise engineering work and 2) how to foster and assess the achievement of learning outcomes in interdisciplinary learning curricula. For higher education, the implications focus on 1) how to sustain progress in intellectual development and on 2) how to foster and assess the progress of intellectual development.

# 8.2.1 Implications of theoretical contributions related to epistemic practices

The theoretical contributions highlighted in section 8.1 have profound implications for the design and implementation of interdisciplinary teaching and learning:

 Firstly, the theoretical contributions towards a practice-based theory of interdisciplinary learning inform a practice-based approach to developing readiness for interdisciplinary engineering practice. It is not enough to provide students with repeated exposures to interdisciplinary problems without also facilitating their repeated engagements in knowledge practices, especially the four epistemic practices that have been shown to be of relevance to engineering practice.

More generally, adopters of an interdisciplinary approach to higher education should also seek to assist students who are less intellectually developed, especially 'dualistic learners' to progress through the various stages of intellectual development by facilitating their engagement in knowledge practices, especially the four epistemic practices.

By facilitating 'dualistic learners' to take ambiguous knowledge suggestions into a series of consultations with a range of experts, such as professors and practitioners from different disciplines, they could learn to initiate efforts to resolve ambiguity and reducing uncertainty. During these consultations, students should be encouraged to make use of their prior knowledge as an analogy in order to motivate engagement with new knowledge. At the same time, they would witness the variety of opinions on the relevance of the knowledge suggestion as well as the variety of counter suggestions, some of which can conflict with the others. This is likely to result in more ambiguous, rather than 'dualistic', answers to their questions, and thereby showing them that disagreements can exist even among experts. Some experts can facilitate progress in learning by suggesting further engagements in knowledge practices, such as 1) adapting and contextualising knowledge to make them more relevant to problems, 2) testing for its relevance, or 3) making a criteria-based comparison of their relative usefulness to problems. This demonstrates to students that they can proceed to learn in a variety of ways in order to reduce ambiguity and uncertainty in knowledge relevance. In short, they should be encouraged to view learning beyond acquiring knowledge from others.

Therefore, engagements in consultations that provide students with suggestions of knowledge practices, rather than with 'dualistic' answers, can be useful for their intellectual development. It can be used as an opportunity to encourage them to gradually relinquish their dualistic view of knowledge as right-or-wrong and to accept a contextual and relativist view on knowledge. At the same time, they can gradually develop commitment to knowledge practices, especially the
four epistemic practices that are more likely to lead to knowledge integration. When they realise that engagements in knowledge practices could have positive implications for knowledge integration, their commitment for knowledge integration could increase further.

- 2) Secondly, however, since the theoretical contributions towards a contingency theory of interdisciplinary learning have shown that engagements in epistemic practices are contingent on a number of different situations, including the perceptions of barrier, it implicates that instructors should not simply dictate engagements in a specific knowledge practice without knowing their students perception of the situations. Instead, instructors should ensure that engagement in any knowledge practice should result from students' efforts to analyse and perceive different situations. More generally, students should be encouraged to engage in situational judgement for choosing knowledge practices that could help them progress along the levels of intellectual development. To promote commitment to integrate knowledge and develop intellectually, it is therefore recommended that situational analysis and judgement on the most appropriate knowledge practice should form a necessary part of interdisciplinary teaching and learning in engineering education specifically as well as in higher education more generally.
- 3) Thirdly, since the perceptions of various barriers and difficulties are prevalent in interdisciplinary learning, it is important to create awareness of their occurrences in interdisciplinary classrooms and at the different stages of intellectual development. More importantly, students should be trained to become adept at overcoming those barriers and difficulties by repeatedly orientating themselves into the enabling modes of epistemic engagement. However, since the barriers and difficulties depend on the individual perceptions of situations and on the individual development needs, it is recommended that instructors should first seek to interpret and validate the type of barriers or developmental difficulties faced by students before intervening with suggestion for orientation into one of the five modes.

### 8.2.2 Implications of theoretical contributions related to outcomes

With the establishment of the relevance of the notion of 'selective, integrated understanding', and the four learning outcomes that constitute it, to interdisciplinary engineering practice, it implicates the need for promoting and assessing the attainment of these outcomes in educational settings.

1) Firstly, these constituent outcomes need to be expressed in a form that is amenable to summative assessments of students' readiness for interdisciplinary practices and of their stages of intellectual development. Table 8.1 below translates the four outcomes into the corresponding abilities that can be assessed summatively at the end of a course or a program.

Constituents of 'selective, integrated	Assessable abilities
outcome'	
Knowledge Adoption outcome	Ability to understand, appreciate the
	importance of, and reuse the relevant
	knowledge of other disciplines while retaining
	its original contents and meanings
Knowledge Translation outcome	Ability to develop and use knowledge whose
	terms and forms are usefully different from,
	but correspond to that which is used in, or
	provided by, the other disciplines
Knowledge Avoidance outcome	Ability to avoid pursuing the learning and use
	of suggested knowledge contents and forms
	that do not contribute to the successful
	development of the solution
Knowledge Addition outcome	Ability to add knowledge that is new to the
	collaborators from other disciplines and
	evidently useful for improving their practices

Table 8.1: The four learning outcomes and the corresponding abilities

- 2) Secondly, the dependence of the four outcomes on prior occurrences of learning pathways has a profound implication for the summative assessment. It implicates the need to complement summative assessments with formative assessments that foster and assess the gradual development of learning pathways. Thus, the various parts of the learning pathways should be translated into 'intermediate learning outcomes', a set of leading indicators of student progress towards the final learning outcomes. For example, one part of the learning pathway that identifies the 'justificational mode of epistemic engagement' can be translated into an assessable statement of 'ability to inquire into the different justifications to knowledge suggestions'. By promoting and assessing their achievement of the intermediate outcomes prior to the summative assessment of the outcomes, instructors can track progress in learning and deploy interventions in a timely manner. This would progressively increase the likelihood of achieving the final outcomes.
- 3) Thirdly, the decisions on what, and how, knowledge could be acquired, translated, avoided or added are largely undertaken emergently by the learners themselves. This implicates the need to give autonomy to students during interdisciplinary learning and to tolerate changes in their decision-making. Therefore, interdisciplinary approaches to learning in engineering education specifically, and in higher education, generally needs to embrace some form of self-determined approach to teaching and learning, also known as heutagogy. By embracing heutagogy within the interdisciplinary approach, instructors can relinquish ownership of the learning process to the learner, who autonomously determines what and how knowledge will be learnt as well as when and why the determinations should change.

## 8.3 Outputs of the research

In addition to the contributions to theory and practice, this research has been disseminating its outputs to the engineering education community through publications and presentations. Table 8.2 lists these outputs.

Research Outputs	Avenues and dates
Mahmud and Ridgman (2014) is a conference paper and presentation that came out from the first year of the PhD research, which identified the need to understand how engineers practise interdisciplinary learning in engineering practice.	<ul> <li>42<sup>nd</sup> Annual Conference of the European Society for Engineering Education (SEFI 2014) in Birmingham, UK.</li> <li>16 to 18 September 2014.</li> </ul>
Mahmud and Ridgman (2015) is a conference paper that reported the preliminary findings of this research.	6 <sup>th</sup> Research in Engineering Education Symposium (REES 2015) in Dublin, Ireland. 13 to 15 July 2015.
Mahmud et al. (2017) is a conference paper and presentation that reports on the application of both the socio-material perspective of learning and the ANT- analytical framework for the purpose of sustaining learning in an interdisciplinary engineering capstone design course that I had coordinated while writing the last chapter of this thesis.	7 <sup>th</sup> World Engineering Education Forum (WEEF 2017) in Kuala Lumpur, Malaysia. 13 to 16 November 2017.
Mahmud and Ridgman (2018) is a conference paper and presentation anticipated in September 2018. I will report the summary of the findings of this research.	To appear at 46 <sup>th</sup> Annual Conference of the European Society for Engineering Education (SEFI 2018) in Copenhagen, Denmark. 17 to 21 September 2018
Mahmud and Ridgman (2019) is going to be a book chapter that has been accepted for publication in 2019. It will draw some lessons from the findings reported in this thesis, and will propose how to make higher education learning more interdisciplinary.	To appear in "Redesigning Higher Education Initiatives for Industry 4.0" edited by Arumugam Raman and Mohan Rathakrishnan, and published IGI Global.

# Table 8.2: Outputs of the research

## 8.4 Limitations of the research

Even though there are significant contributions to theory and profound implications for educational practices, the extent of the theoretical contributions and practical implications are affected by the limitations of the research.

The first limitation is in the approach to identify the knowledge practices. It has relied largely on the empirical traces gathered in interviews and in archived documents, rather than complementing them with the observation of practitioners at work. It is likely that some other practices could not be identified perhaps due to the limitation in the life-time, availability and accessibility of their empirical traces. As a result, the range of practices identified is likely to be limited. It can be criticised that the comprehensiveness in its contribution to a practice-based theory of interdisciplinary learning is still lacking.

Secondly, the research could only specify variables that are necessary, but insufficient, by themselves or in combination, for the occurrence of the different aspects of the phenomenon. This limits the assertion in that the perception of barriers, the orientations into the modes, and the activation of the mechanisms would make the corresponding engagements in epistemic practices and the achievement of learning outcomes, more likely rather than definite. Thus, the findings could not be used as a means to predict the occurrence of the different aspects and relationships embodied in the theoretical framework. Further, the learning practices could not be promoted in a prescriptive manner since they are contingent on the situational perception of individual learners. As a result, this research can only prescribe engagement in situational diagnosis and discretionary use of the knowledge practices according to the individual perception of situations encountered.

Thirdly, even though the findings that provide the constituent outcomes of the 'selective, integrated understanding' can inform the formulation of assessable abilities, they are based on a limited number of cases that are anchored, at most, by two main disciplines - engineering and the life sciences. The level of complexity of the problems/issues addressed by the two disciplines involved is not as high as that of other interdisciplinary problems requiring three or more disciplines. Other interdisciplinary collaborations that involve experts and practitioners from three or more disciplines for addressing more

complex world problems might contain a wider range of learning outcomes that constitute the notion of 'selective, integrated understanding'.

Fourthly, the comprehensiveness of the typology and learning pathways achieved by this research is limited since they are constructed from studying a limited number of cases within one sub-class. Therefore, the formulation of the intermediate outcomes that are amenable to formative assessments is likely to be limited. Furthermore, in educational contexts there are likely to be other enabling and counteracting mechanisms that are not present for identification in the workplace settings. The existence of these mechanisms might implicate the occurrence of other learning pathways.

With the recognition of the contributions, implications and limitations of this research, it is now timely to set the stage for the recommendations of future research. The next section recommends some research areas that can build on the significance of the current contributions as well as improve on the current limitations.

# 8.5 Recommendations for future research

This research opens up a number of interesting areas for future research and educational activities. The following subsections discuss them in the order of priority.

# 8.5.1 Studying ongoing cases of interdisciplinary learning in interdisciplinary collaborations

An interesting investigation that could complement this study of completed cases is a study of ongoing cases of interdisciplinary collaborations. It has the highest priority since it could help complement the main limitations of this research, which are the lack of observation of the actual learning practices and a heavy reliance on retrospective interviews. Therefore, such a study should prioritise on observing the learning practices of engineering and non-engineering professionals at the actual sites of interdisciplinary collaborations.

Preferably, a study of ongoing cases should be carried out as one large-scale longitudinal research covering all the four stages of interdisciplinary collaboration conceptualised as the sociology of translation. As well as conducting observations and interviews, the data collection could also include focus group so that alternative descriptions and explanations could be entertained.

Alternatively, a small-scale short-term study could select any particular stage of the 'sociology of translation' process, such as the 'problematisation' stage, and identify learning practices that occur in that stage. At an even smaller scale, researchers could engage with an ongoing interdisciplinary collaboration for a short duration, study the learning practices, and characterise the stage accordingly.

The combination of large- and small-scale studies could lead to a cumulative understanding as well as to the adjudication among alternative descriptions and explanations.

One advantage of researching ongoing cases might come from the opportunity to encounter more complex form of interdisciplinary collaborations. Researchers should grab any opportunity to study interdisciplinary learning practices that occur in interdisciplinary collaborations that address highly complex problems and opportunities, for example those that relate to the fourth industrial revolution. It is likely that such complex collaborations involve a greater number of disciplines, and therefore provide an opportunity for the researcher to compare the learning practices across several disciplines.

Research on ongoing cases of interdisciplinary collaboration could adhere to the practice-based approach for theorising professional learning. Their results could cumulatively increase, if not exhaust, the range of learning practices identified. To support accumulation of knowledge and comparability of the results, it is recommended that researchers adhere to the critical realist framework of data analysis so that the description and explanation of interdisciplinary learning phenomenon could move closer to the actual reality.

### 8.5.2 Replicating the study in educational settings

Another high priority area of research would be to replicate the study in educational settings. Preferably, the study of interdisciplinary learning in educational settings should engage ongoing cases of interdisciplinary student projects, such as interdisciplinary engineering capstone design projects. As well as describing and explaining learning practices that result in the desired and undesired outcomes, such as study should also seek to identify other personal, curricular and institutional contingencies that could increase, if not ensure, student engagements in the learning practices and the achievements of outcomes.

With the larger scope of factors related to those personal, curricular and institutional contingencies, researchers can include alternative inferences sourced from other non-learning perspectives. As well as increasing the analytical rigour, this can also increase the applicability of the theoretical framework to the educational setting.

These descriptive and explanatory studies could be usefully followed by action-research type of studies. Researchers can implement and then evolve the proposed theoretical framework into one that could be used to support and sustain learning in educational settings.

### 8.5.3 Studying less successful cases of interdisciplinary collaborations

Another less priority, but theoretically useful, research area is a study of past interdisciplinary collaborations that have failed to create, or sustain, solutions to problems that they had attempted to solve. These can be called less successful, or 'negative cases'. Although they cannot be prioritised highly due to the overreliance on retrospective views of the informants and the possible lack of data for validating inferences, they could still be theoretically useful for the current theoretical framework.

If the variables that describe and explain the successful cases are absent from the 'negative cases', then our confidence in the proposed description and explanation could be increased. Since access to data on such cases would be difficult for non-participant researchers, researcher should try to become 'participants' in interdisciplinary

collaborations and keep documentary evidences easily accessible for comparing between cases of less successful and more successful ones.

## 8.5.4 Applying the framework to educational activities

Even though the theoretical framework has some limitations, it can be applied to inform the design and implementation of some educational activities.

The highest priority application is for engineering educators to help sustain students learning in interdisciplinary projects. These projects tend to be problematic due to the barriers that could arise when students from different disciplines interact, but also when they interact with project facilitators and potential users from other disciplines. Nevertheless, these kind of projects usually target to develop the higher order skills and intellectual development such as evaluation and synthesis. Therefore, educators must be ready to support and intervene when necessary learning is derailed by the barriers.

In particular, coordinators of these projects could use the theoretical framework in consultation with the students to diagnose the type of barriers that confront them. They could then attempt to apply the suitable mode of epistemic engagement to overcome those barriers.

Another interesting application is to apply the theoretical framework to describe and explain interdisciplinary learning that occurs in co-curricular activities. This recommendation is inspired by the recent revelation by Lattuca *et al* (2017) of the significant and positive correlation between engineering students self-reported interdisciplinary outcomes and their involvement in co-curricular activities, especially in non-engineering clubs and organisations, overseas study, and humanitarian engineering projects. Their study suggests that these activities are likely to help students build interdisciplinary skills, but does not describe or explain how that could happen.

As the design and implementation of educational activities in the institutions of higher learning are becoming more innovative, we could expect to see more avenues for applying and evolving the theoretical framework proposed by this research.

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# Appendices

# **Appendix 1 Evidence Statements**

1 INFORMANT C

Evidence Statement 1 "we got engineers who understand engineering processes and they understand things like you know...tolerances...biological processes aren't defined in the same way... you're saying bits and Bytes and they're saying you know sort of Carbon Dioxide and Glucose".

Evidence Statement 8 "what the life scientist is bringing is what the engineers learn...what life scientists can do is to say why you have to do it like this, can you suggest a biologically relevant alternative? Not why don't we just boil the cell to sterilise it."

Evidence Statement 11 "being able to translate between the customer and the engineer, so [life scientists] can say what they want in their own language but not as an engineering specification."

Evidence Statement 15 " they have no idea, they're thinking in engineering terms and they don't have necessarily any appreciation of what is critical or not critical, what's important, why it's important that you don't have any particle, why is it important you don't do this out of the other...there's a difference between the process as you describe it and the process as somebody hears it, who doesn't have the knowledge. There is a gap like this [hand gestures]...they will say lots of things with lots of assumed knowledge, if you don't have the same knowledge level, you don't really know what they mean, you heard the words but you can't interpret their meaning"

Evidence Statement 16 "I said oh we could do that, I'd done cell culture it's my bio background, I'm a Biochemist. Therefore, I came back, and I said that's not electronics but we found this opportunity what do you think. Of course, nobody back then has any idea what cell culture is I said. It's not that hard really; you know it might be possible to automate it. So, this was the result - we develop the first automated cell culture robot

Evidence Statement 17 "My colleague [Informant A] said we're going to do automation for the electronics assembly...Of course, nobody back then has any idea what cell culture is. I said, it's not that hard really, you know it might be possible to automate it. So, this was the result - we develop the first automated cell culture robot. We were not constrained, we were able to bring experiences and technologies from other industries, you know clean robot comes from the chip manufacturing."

Evidence Statement 21 "they can ask the life scientist to say what would be important or we got these two potential ways of doing it which do you think would work, and then also I can say, the customers aren't gonna like that. Why not? Because duh duh duh duh duh".

Evidence Statement 22 we could say, why did you do it like that? And that helps because you then you're not constrained to do things the same way that they are always done".

Evidence Statement 23 : "What was interesting to say was that the process was very well controlled because robot was doing it; they were then able to apply statistical analysis a bit changes and how to improve product yield".

### 2 INFORMANT A

Evidence Statement 2 "We did very quick simulations of what might be needed, we did a quick sketch...we wrote a report that says this is how we should do it...and they said OK, off you go" [Informant A], and

Evidence Statement 4 "you're told that Cell Culture is an unstable, difficult process, where you have to have `green fingers' as they talked about. You do something slightly different to the cells, they won't do anything you expect them to you see, and we kind of nodded and said yes we understand it's very difficult etc. etc., but in reality we didn't believe a word of it...and we took some video cameras into the kind of manual facility and watched what they were doing, and actually you know they were just emptying and filling in bottles...they kind of said oh they are very sensitive to vibration and shock, you know, when the supervisor wasn't there they were throwing them around like coke bottles. We kind of use that consulting thing ...that we are going to take all their concern seriously, but actually in the back of our mind we were rationalising this down to something very straight forward...we said oh yeah it's a robot, so if the things go too fast, we can always slow the speed down, you can slow things down when used with real cells. We test the machines as fast as we could possibly made them go, we said this is the

fast that it can be possibly go but of course it may not be right if you start putting real cells. They never turn them down at all, first run all perfect."

Evidence Statement 5 "We discovered, one like key learning, I guess, is that most of these processes do not have tolerance with them. They kind of said you incubate it at 37degree...and you kind of said plus or minus what? They said no...it says 37 degree, there it says on the dial...It's all being an open loop actually. So they say what are you going to do under this circumstances, and we say, well you measure everything and do a QbD type of thing, and identify the key parameters, and produce 17 dimensional surface, and say that's your sweet spot, so if you operate within the tolerance of the sweet spot, you can't possibly fail kind of thing, and to some extent you kind of have to keep that at the back of your head because as far as they were concern, it was an impossible process that was magic. You can't make this guys look stupid, you have to kind of what we describe as `bedside manner'...like doctors learn how to talk to patient without frightening them. It's about communication. It's about appearing confident, without kind of asking questions and don't get the answers that you want or cause people to worry... We did a little bit of analytical work with [the company], to kind of get some numbers 'cause we tried to get some sort of tolerances in the process parameters"

Evidence Statement 18 "...we took some video cameras into the kind of manual facility and watched what they were doing, and actually you know they were just emptying and filling in bottles...we could have been sitting with experts, cell culture people who'd say very difficult, the cells are very difficult, etc. as oppose to ...looks like emptying and filling bottles, which is what it really was".

Evidence Statement 20 "...They have this manual method, it's just fine, but it was not a high throughput...The question was can we do this with some robots, or something. So we went back, we kind of got basic understanding of what they wanted to do...We did some very crude calculations, we did some very quick simulations of what might be needed, we did a quick sketch, and we said we'll built you this for half a million. We wrote a report that says, this is how we should do it, this is what it's gonna cost, we could get it going for six months and they said ok, off you go you see...and so we took a fairly pragmatic approach...and crudely we sketch some machine up, drew them up and

built them, we ship them to Slough, where the facility was and they work first time. It was a very great surprise cause the thing was you see cell culture has always been described as sort of art-and-craft; you know that you do something slightly different to the cells, they won't do anything you expect them to you see.

### 3 INFORMANT B

Evidence Statement 3 "So what we did was we built a machine that took a roller bottle and added some liquid in, the liquid was water, we did all the movements but without any cells in and the customer said that's great, ship it to our facility and we'll put cells in it, and they put cells in it, and it worked" [Informant B].

Evidence Statement 6 "when we came to testing it quite often we test the equipment with water on our site, but then we might want to grow some cells and if the cells don't grow properly, the Software Engineer who sat there with the biologists and looking at the results; why it is not happening ? What can we do? Can we change the software, can we do this? Can we do that to make it all works"?

Evidence Statement 7 "the main thing we needed to do is make sure that the thing were done sterile, so we needed to understand about sterility"

Evidence Statement 9 -we were just getting a robot to do what a person would do...you actually watched people doing the process and say OK, now what you're doing is taking the bottle, you're adding some liquid in, and you shake it, and putting the cap back on,...and you can understand and automate that".

Evidence Statement 10-"we had a couple of people like [informant C] who have a life science background so they could help, they understand the users' needs"

Evidence Statement 13 - "One thing that we do is we would typically tend to go to meetings together [Researcher: Meeting with the customers?] Yeah yeah,... they'd say, I want our process to do this and this, and as an engineer I go, ok, well how many samples per hour do we need, what's the volume, what accuracy do you need, and a lot of time when people describe their process they don't talk about these sort of things...they talk about molecular biology that I don't need to know as an engineer and what I need to know is how many samples an hour we're gonna need to be processing, what steps I

would need, add some liquid here, take some liquid out there, I need to do a measurement here, what the biological reactions are I'm not really interested, I just need to add compound A and compound B and get reaction and then I measure the results and I have to design a piece of equipment that does that. I don't need to know all the ins and outs like the molecular biology."

Evidence Statement 14 - we do all the movements but without any cells in and the customer said that's great, ship it to our facility and we'll put cells in it, and they put cells in it, and it worked".

Evidence Statement 16 - "they start using the whole words, all things about Biology that we wouldn't recognise, we wouldn't be able to communicate as well... they'd say, I want our process to do this and this, and as an engineer I go, ok, well how many samples per hour do we need, what's the volume, what accuracy do you need, and a lot of time when people describe their process they don't talk about these sort of things"

Evidence Statement 12 "when we went and talked to customers, they'd say, I want our process to do this and this, and as an engineer I go, ok, well how many samples per hour do we need, what's the volume, what accuracy do you need, and a lot of time when people describe their process they don't talk about these sort of things...they talk about molecular biology that I don't need to know as an engineer and what I need to know is how many samples an hour we're gonna need to be processing, what steps I would need, add some liquid here, take some liquid out there, I need to do a measurement here, what the biological reactions are I'm not really interested, I just need to add compound A and compound B and get reaction and then I measure the results and I have to design a piece of equipment that does that. I don't need to know all the ins and outs like the molecular biology. So those are the sort of things you need, you then starting moving mind to sort of engineering sort of terminology, whereas Biologist say I add A to B, I made my chemical, or my molecule or whatever that might be , and that's how they think but we then need to translate it to slightly different way of thinking".

Evidence Statement 19 "...when you got some equipment generating some data, how do you want that data out, what format, what sort of user interface you want, you now got a

piece of automated equipment, rather than doing things in test tube, bench, you now got a computer system, you need to interact, you need to tell the machine what to do to process your samples through, so what user interface you want. And not the sort of things that customer users think about. Sort of things important to design a machine".

Evidence Statement 24 "when we came to testing it quite often we test the equipment with water on our site, but then we might want to grow some cells and if the cells don't grow properly, the Software Engineer who sat there with the biologists and looking at the results; why it is not happening what can we do? Can we change the software, can we do this can we do that to make it all works."

#### 4 INFORMANT E

Evidence Statement 25 "Also talking to them again, they say well actually if we can find a better feed strategy not necessarily to produce more titre but actually cheaper feed, that can mean our bottom-line, some of the feeds are really expensive in a 2000 litre tank...because what they're saying is, we want to try to find the best feed strategy, cause if we can try 6 different feed strategy, 6 different feed and find actually this one here is cheaper but produce either the same or similar titre, that'll be really good for us...they just discussing how they would be using "ambr" [the nick-name for the automated micro-scale bio-reactor] in order for them to try to work out their process, may be cell line selection,...but also it might be media optimisation, finding which is the best media...they tell me what sort of things they want ..and why.. Why do you want to do this? Usually you want to do this to get more of your titre or more product at the end or to get the same amount of product but cheaper or to find the best cell line to produce the product, and so it's learning why people are using bioreactor not necessarily the fact that there's a piece of glass with the impeller you're pumping stuff in, DO and pH, that's the physical thing of what you are doing but why you're doing it...so I would go into their lab, so I would see how their labs were set up, and often talk to them what was their processing, what they were trying to do, and so therefore because they would have

never seen an "ambr" before, they would start talking about what their processes were , I have then try to relate what "ambr" could do what their process could do".

### 5 INFORMANT F

Evidence Statement 26 "So two things I'm going to pick up a lot as we go through this I expect, the way that we work here we co-seat (i.e. co-locate)...so we were sitting very close to [Informant G], our business development guy who himself used to be biologist, sitting right next to me. Secondly, my wife is a biochemist and all the people I went to uni with, my social group tend to be biochemist...so talking about the general process probably came a lot from my wife, and then half of that from people like [Informant G], our business development people".

Evidence Statement 29 "Of course you wrote some software programmes that allow you to express a process. So, then I had to help the customer express their processes in the language which we had defined. Help the customer represent the process that was a minor thing back in those days as I was still fairly junior then...that was probably the main place where you start to sort of want to understand in a very simple way the biological process."

Evidence Statement 31 "We were, although naively, but were acting like users at that point, so I mean that's the point where the hardware people have tested that and when you tell this motor to go to this and this position, it does, there you go software guys and then we put software on. That's the point we really actually trying to get the machine to do what it's supposed to do. That is the point we need to know what they are trying to achieve, you need to know what the machine is for...what success looks like, you know what does 'working' look like...indeed "ambr" is a research machine, it is not a manufacturing machine"

Evidence Statement 34 "You do want to understand the mind of the customer as good as you can, you want quite broad but shallow knowledge I suppose, once you got the idea of the process that goes through sort of the recipe what they are doing, hardware and software is all about making interfaces, we tend to have the same way in the way we think , to separate this what it's doing to cell, and then ultimately it's just moving plastic around, because you know that is just the interface between the actual problem and the problem that you're trying to solve. I do like to understand what their problems that the machine try to solve, understand from in their framework, in their sense. At the same time I don' feel the need to go and read academic papers about what they're doing. [Researcher: Why?]. It's the only way to... once you sort of have this effort try to define what the process is so we eventually worked out you need a robot that does xyz and it does xyz and you could go off and do the robot".

### 6 INFORMANT D

Evidence Statement 27 Informant D: "so my task in the design study was to create like concept of what the automated-micro-bioreactor system might be. So the idea put forth to me was something in a micro-titre plate format because that was on the market already and I started to look at that but no, it's not really going to work, plus there was this rather subjective view that we should have a stirred vessel because something in the micro-titre format is not really like a bioreactor. There's a subjective view that it needs to look and feel like a bioreactor, need to be seen as having the feature of the large bioreactor with sparged tube and impeller and pH measurement and dissolved oxygen, temperature control, a small bioreactor with features of the large bioreactor that overcomes a hurdle in peoples mind about buying a small bioreactor, whereas if you got shaken plate or flask which was the established way of small scale culture they are not the same as a bioreactor; they don't have the same performance. So part of the requirements was to perform in similar way to a larger bioreactor; it should also look like it." ... We could easily said what's the easy way: something to shake a microplate and create a shaken microplate system and that probably would have been a failure because it was just like what's there already; we needed something different."

Evidence Statement 32 "Having talked to the customer, we felt the need for a larger volume bioreactor, because the amount of product you could get from [the first system] you got a small volume and I understand [the first system] is for mammalian culture, we had two customers who were interested in microbial culture, and I understand microbial is higher producer of protein of interest, need a larger volume to get enough product, so we thought that a 250ml volume would probably be sufficient,

### [Researcher: Does that entail you having to learn more about microbial?]

"Yes, it was. So, from starting again understanding the bioreactor climates for microbial culture, such as the bioreactor geometry of the bioreactor, what are the requirements that would meet the scale up requirements such as KLa, in volume, there is no standard geometry for bench-top bioreactors. There's a big difference between mammalian culture and microbial culture. So, I design the vessel that tries to get the middle ground between mammalian and microbial. And there's the other challenges that microbial culture you have to stir it very vigorously, and there's a lot more heat generated therefore more heat has to be dissipated, so much more challenging than a mammalian culture"

[Researcher: How did you learn all these?] One of our lead customers telling us what kind of issues could be, what the challenges are, we make some prototype image, we test until we understood the problem and work out a working system."

Evidence Statement 35 "So the idea put forward to me was something in a micro-titre plate format because that was on the market already and I started to look at that but no...it's not really going to work, plus there was this rather subjective view that we should have a stirred vessel because something in the micro-titre format is not really like a bioreactor; there's a subjective view that it needs to look and feel like a bioreactor, need to be seen as having the feature of the large bioreactor"

Evidence Statement 37 "In Mechanical Engineering you get used to making component to within 10microns or a few microns, very high accuracy and in manufacturing process the machine, everything, makes exacting process. Biology, by contrast is sort of a bucket of this and a bucket of that and its quite low relative to the precision in many engineering processes, it's getting more and more, but relative, if you look at the growth curve of cell, anything within plus minus 10percent around sort of the average is fine. And so coming from a mechanical engineering mind-set we were thinking about accuracy of plus minus, 1 percent or 2 percent....that's not good, that's pretty poor. However, bringing automation to the biological process start bringing a lot more consistency, you start to see the effect of 5percent less liquid, 5percent less growth, now that their graphs go tighter and tighter...if you got a spread like that, if you got something where all the lines, and one down here, you know that's an anomaly".

#### 7 INFORMANT K

Evidence Statement 28 "If I take the mechanical part, which is when we do the stand, the wheels, you have to understand the centre point of the wheel, this test of threshold, 20cm is the centre point of my wheel...there is also 20mm rule before, that is too close to the centre of the wheel, the wheel struggles to pass over when you got over 45kg. So understanding that principle you know that's too close to the centre of the wheel, if you understand that then you can redesign around it, and design around is to put a bigger wheel on, not too big, ..., if I do a 100 and it went over 33, so I'm not going over a 33mm threshold, so 20mm threshold over a 100mm wheels will pass and it passes easily. Simple things like that is just experience and knowledge of different parts of engineering"

Evidence Statement 30 "And I just started to do that test because …..I was pushing it through the doorway…because it's a safety test. The old test was a 20mm threshold, but it was wrong and I just knew that it's a technical failure. Its 10mm, nobody has 20mm threshold, so we passed with those wheels when we redesigned to have a bigger wheel, and that caused a big problem cause it wouldn't go underneath the bed, so the small wheels would go underneath the bed. So you got to think about these things when you do the design."

Evidence Statement 36 "There's more in the software, it used to be just the basic recorder of chest movement, now we tell people we have data output that they shown out which they couldn't do before. We're coming up with more data that we capture and it's just the matter of analysing that, rewriting the software, and to present it. That's a challenge but at the moment we can tell you the ratio performance of your left lung as compared to your right lung, which nobody else can do, and we do that without attaching to anything, you sit down and we scan you and we can tell you breathe from your lungs using the muscles of your lung or you breathe from your diaphragm, if you are a COPD patient which chronic obstructive you tend to breathe more from the diaphragm, cause of the disease in your lung, nobody else can do that, which is why it's taken off really well, but to do that we have to collect a lot of data and rewrite software and believe it or not we have the dumbness of the American market, so to get FDA application we have to take all that research over our software".

### 8 Informant L

Evidence Statement 33 "In here I generally liaise with the clinical manager here, so that's my first point of contact, and basically she's the one who kind of manages me...Often, here I liaise with two clinical managers we've got, basically they tell me what they need and try to produce that... In terms of knowledge, yes both of them are sort of clinicians they are into it a lot more than I do, so yes, and in that sense I have and I can talk to them about the biology things that I don't understand ...One thing which really helps me is my PhD was in biology background so I do have a little bit of biology background that helps me a lot, if I didn't have that everything here would have been new to me, because I worked a bit with respiratory signal before that helps me a lot, I know the signals I know the pattern it's just , it's a great help. If I didn't know that I would have had to spend a lot of time sort of talking to them, reading this textbook to understand what is it that they want me to do"